ELECTRONICS I

SUBCOURSE MM0705

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US Army Ordnance Missile and Munitions Center and School

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INTRODUCTION

The most important single device in electronics is the vacuum tube. Facts have established that without it, present day knowledge of this science would have been impossible. The first radio receivers used no vacuum or electron tubes. They used a crystal semiconductor as a rectifier (detector) in conjunction with a coil and a variable capacitor for maximum signal. However, radio, radar, and electronic computer equipment employs a wide variety of vacuum tubes.

This subcourse discusses the various types of vacuum tubes commonly used in radio and electronic circuits. You will learn about tubes with only two elements (diodes), tubes with three or more elements (triodes, pentodes, etc.), and specially designed tubes called special purpose tubes. In addition, you will learn about power supplies that furnish energy for the operation of these tubes. What you learn about vacuum tubes, transistors, and power supplies will largely determine how much you will be able to understand about radio and radar circuits.

Supplementary Requirements

There are no supplementary requirements in material or personnel for this subcourse. You will need only this book and will work without supervision.

Credit Hours

Nineteen credit hours will be awarded for the successful completion of this subcourse--a score of at least 75 on the end-of-subcourse examination.

Administrative Instructions

Change Sheets. If a change sheet has been sent to you with this subcourse, be sure you post the changes in the book before starting the subcourse.

Errors on TSC Form 59. Before you begin this subcourse, make sure that the information already typed on your TSC Form 59 (ACCP Examination Response Sheet) is correct. You will find the correct subcourse number and subcourse edition number on the front cover of this book. If any of the information on your TSC Form 59 is incorrect, write to:

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Correspondence with IPD. In any correspondence with IPD, always write your name, Social Security Number, and the school code of your enrollment on each page.

Grading and Certification Instructions

When you have completed the subcourse, review any of the material covered that you are not sure of. Then take the end-of-subcourse examination. When you have completed the examination in the book, you must transfer your answers to TSC Form 59. The instructions on the form itself tell you how to mark your answers on it. Follow the instructions carefully.

Once you have transferred your answers to the TSC Form 59, fold the form as it was folded when sent to you. Do not staple or mutilate this form! Place the form in the self-addressed envelope provided and mail it to IPD. No postage is needed. TSC Form 59 is the only material that you are required to return to IPD. If you return it as soon as you have completed the subcourse, you will get your next subcourse sooner.

Grading. The highest score possible on the end-of-subcourse examination is 100. The grade structure for all ACCP subcourses is given below:

Superior	95-100
Excellent	85-94
Satisfactory	75-84
Unsatisfactory	0-74

Your TSC Form 59 will be machine graded, and you will be notified of the results. Your grade on the examination will be your grade for the subcourse. No credit is given for grades below satisfactory (75).

Certificates. When you have completed the subcourse successfully, IPD will send you a subcourse completion certificate. Keep it with your other personal copies of personnel material. Subcourse completion certificates can be used to support accreditation and other personnel actions.

Lesson 1
BASIC VACUUM TUBES

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to describe the fundamental construction, operation, and theory of vacuum tubes.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70% on the end-of-subcourse examination that covers this lesson and lessons 2 through 7 (answer 35 of the 50 questions correctly).

DEVELOPMENT OF VACUUM TUBE

Current flows in the conductor of a completed circuit when a voltage is present, and current and voltage always obey certain laws. In electronics, these laws still apply. They will be used continuously in working with electronic circuits. Electrons flow across a gap, a break in the circuit in which there appears to be no conductor. A large part of the field of electronics and the entire field of electron tubes are concerned with the flow and control of these electrons "across the gap."

Metallic conductors contain many free electrons that at any given instant are not bound to atoms. These free electrons are in continuous motion. The higher the temperature of the conductor, the more agitated are the free electrons, and the faster they move. A temperature can be reached where some of the free electrons become so agitated that they actually escape from the conductor. They "boil" from the conductor's surface. The process is similar to steam leaving the surface of boiling water. Heating a conductor to a temperature sufficiently high to cause the conductor to give off electrons is called thermionic emission. A representation of electrons leaving the conductors surface is shown in figure 1-1.

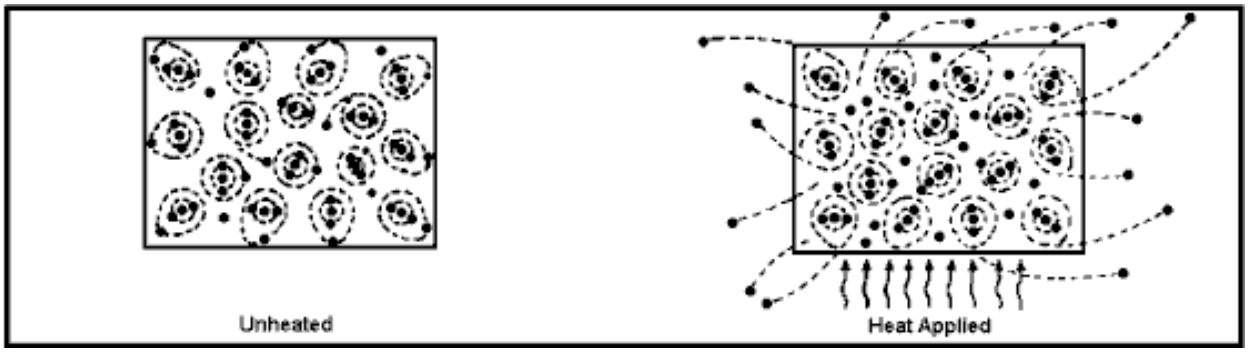


Figure 1-1. Thermionic Emission.

Thomas Edison discovered the principle of thermionic emission as he looked for ways to keep soot from clouding his incandescent light bulb. Edison placed a metal plate inside his bulb along with the normal filament. He left a gap, a space, between the filament and the plate. A battery was placed in series between the plate and the filament, with the positive side toward the plate and the negative side toward the filament. This circuit is shown in figure 1-2.

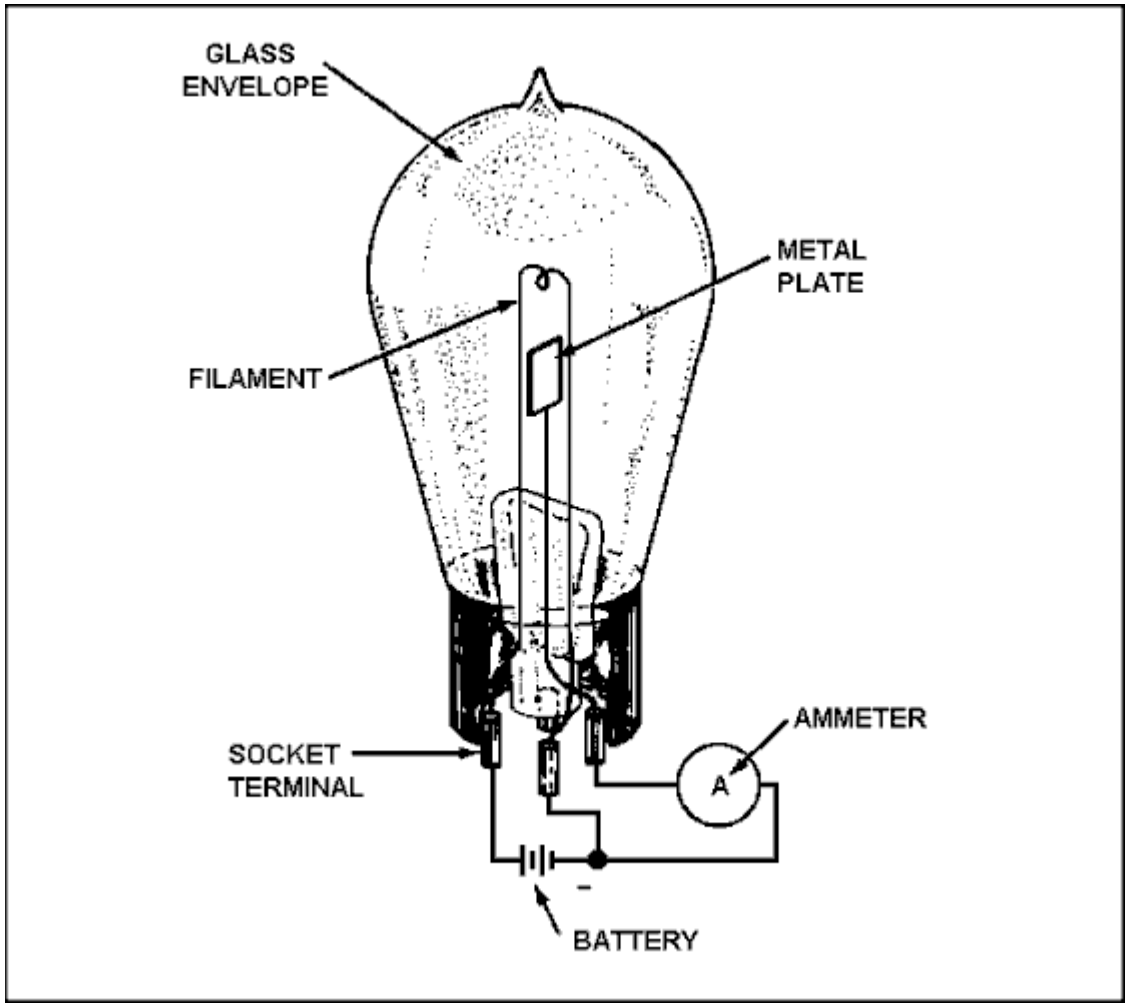


Figure 1-2. Edisons Simple Two-electrode Tube With Plate Negative.

When Edison connected the filament battery and allowed the filament to heat until it glowed, he discovered that the ammeter in the filament-plate circuit had deflected and remained so. Edison reasoned that an electrical current must be flowing in the circuit, even across the gap between the filament and plate. Because this did not eliminate the soot problem, he did little with this discovery. However, he did patent the incandescent light bulb and made it available to the scientific community.

An analysis of the circuit in figure 1-2 shows that the heated filament causes electrons to boil from its surface. The battery in the filament-plate circuit places a positive charge on the plate (because the plate is connected to the positive side of the battery). The electrons (negative charge) that boil from the filament are attracted to the positively charged plate. They continue through the ammeter, the battery, and back to the filament. Electrons flowing across the space between filament and plate are actually an application of the basic law that says unlike charges attract.

Edison's bulb had a vacuum so that the filament would glow without burning. Also, the space between the filament and plate was relatively small. The electrons emitted from the filament did not have far to go to reach the plate. Thus, the positive charge on the plate was able to reach out and attract the negative electrons. The key to this explanation is that the electrons were floating free to the hot filament. It probably would have taken hundreds of volts to move electrons across the space if they had to be forceably pulled from a cold filament. Such an action would destroy the filament and the flow would cease.

The application of thermionic emission, which Edison made by causing electrons to flow across the space between the filament and the plate, has become known as the Edison effect. It is fairly simple and extremely important. Practically everything that follows will be related in someway to the Edison effect.

DIODE TUBE

The diode vacuum tube is really Edison's old incandescent bulb with the plate in it. Diode means two elements or two electrodes and refers to the two parts within the glass container that make up the tube. They are referred to here as the filament and plate. More formally, they are called the cathode and plate, respectively. Sometimes the filament is also called a heater.

A few years after the discovery of the Edison effect, scientists had learned a great deal more than was known by Edison at the time of his discovery. By the early 1900s, J. J. Thompson in England had discovered the electron. Marconi had demonstrated the wireless receiver, which was to become the radio, in Italy and England. The theoretical knowledge of the nature of electricity and things electrical was increasing at a rapid rate.

J. A. Fleming, an English scientist, was trying to improve on Marconi's relatively crude wireless receiver when his mind went back to Edison's earlier work. His subsequent experiments resulted in what became known as the Fleming valve (the diode), the first major step on the way to electronics.

Operation of Diode Tube

Before learning about Fleming's valve, the forerunner of the modern diode, Edison's original circuit will be explained further. This time, however, it will be presented as a schematic diagram using the symbol for a diode instead of a cartoon-like picture. The schematic of Edison's experimental circuit is shown in figure 1-3. This is really two series circuits. The filament battery and the filament itself form a series circuit. This circuit is known as the filament circuit. The path of the second series circuit is from one side of the filament, across the space to the plate, through the ammeter and battery, and then back to the filament. This circuit is known as the plate circuit.

Part of the filament circuit is also common to the plate circuit. This part enables the electrons boiled from the filament to return to the filament. No electron could flow anywhere if this return path were not completed. The electron flow measured by the ammeter is known as plate current.

The voltage applied between the filament and plate is known as plate voltage.

Diode Operation With a Positive Plate. Fleming started with a two-element tube (diode) similar to Edison's and at first duplicated Edison's experiment.

With the plate positive relative to the filament, the filament hot, and the circuit completed as shown in figure 1-3, the ammeter measured a current flowing in the plate circuit. Because current is the same in all parts of a series circuit, the same current must flow across the space between filament and plate. The electrons boiled from the heated filament are negative and are attracted to the positive plate because unlike charges attract.

Diode Operation With a Negative Plate. Fleming's next step was to use a similar circuit but to reverse the plate battery. The circuit is shown in figure 1-4. With the plate negative relative to the filament, the filament hot, and the circuit completed as shown, the ammeter indicated that zero current was flowing in the plate circuit.

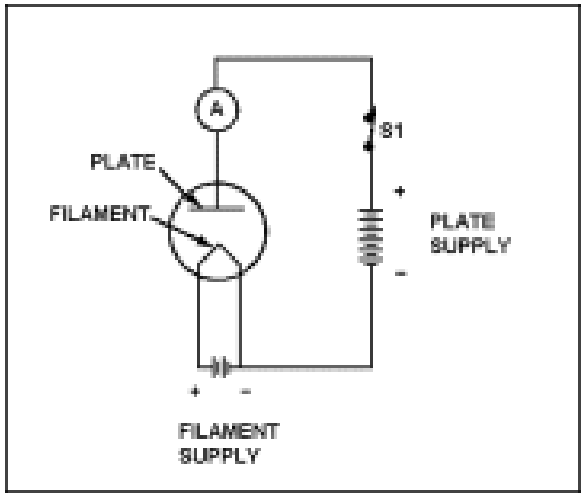


Figure 1-3. Schematic of Edison's Experimental Circuit.

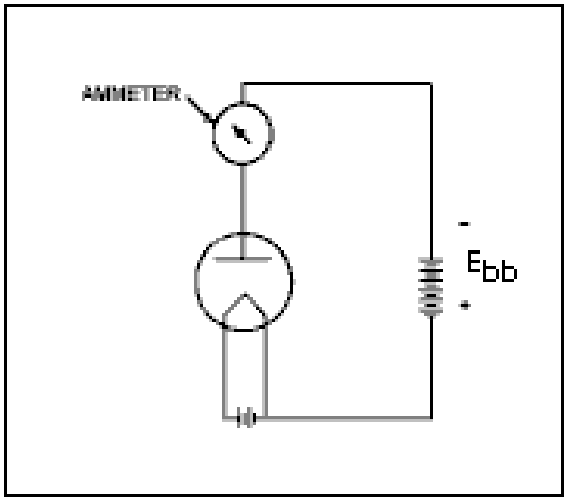


Figure 1-4. Diode With a Negative Plate.

Fleming found that the negative charge on the plate, relative to the filament, cut off the flow of plate current as effectively as if a valve were used to stop the flow of water in a pipe.

The diode cuts off current when the plate is negative for the following reason. The filament is hot and electrons boil from its surface. Because the filament is the only heated element in the diode, it is the only source of electrons within the space between filament and plate. However, because the plate is negative and the electrons are negative, the electrons are repelled back to the filament because like charges repel. If electrons cannot flow across the space, then no electrons can flow anywhere in the plate circuit; therefore, the ammeter indicates zero.

The reason that electrons do not flow from the negative plate to the positive filament under these conditions is the following. It takes a heated element to emit electrons and the filament is the only heated element in the diode. The plate is cold; therefore, electrons cannot leave the plate, and plate-to-filament current cannot exist.

Measuring Diode Voltages. It is impossible to have a voltage at one point because voltage is defined as a difference of potential between two points. In the explanation above, reference was made to plate voltage. Plate voltage is the voltage between plate and filament. Plate voltages are often referred to as if they appear at one point. In figure 1-5, M1 and M2 measure plate voltage and filament voltage respectively.

The reference point in diode and other tube circuits is usually a common point between the individual circuits within the tube. The reference point (common) in figure 1-5 is the conductor between the bottom of the transformer secondary and the negative side of the filament battery. One side of each ammeter is connected to this point.

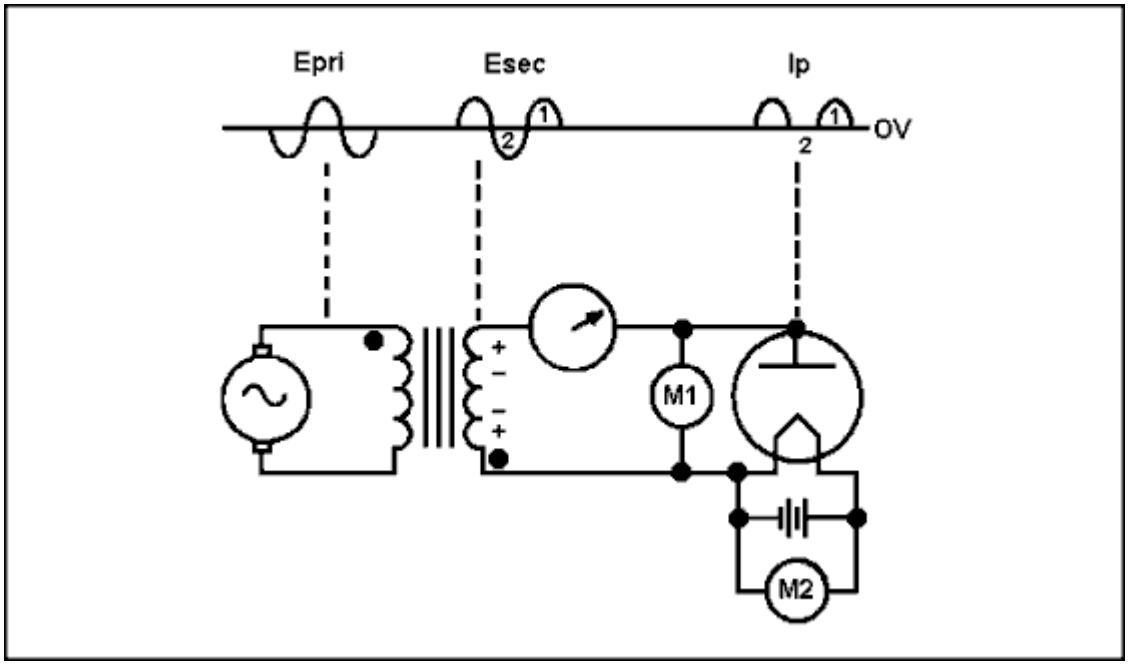


Figure 1-5. Alternating Voltage on the Plate.

Diode Operation With Alternating Voltage on Plate. After experimenting with a positive plate and a negative plate, it was logical that Fleming would replace the direct voltage of the battery with an alternating voltage. In this explanation, a transformer will be used as the source of alternating voltage. The circuit is shown in figure 1-5.

The only real difference in this circuit from the previous ones is the transformer. The transformer secondary is connected in series with the plate circuit where the plate battery was connected previously. The transformer always produces an alternating voltage. The secondary voltage is a sine wave as shown in the figure. The sine wave is a visual picture, a graph of the change in alternating voltage as it builds from zero to a maximum value and then drops to zero again just before it reverses direction and continues in the same manner.

Assume that the polarity across the secondary during the first half-cycle of the input ac voltage is as shown in the figure. During this entire first half-cycle period, the plate's polarity will be positive. Under this condition, plate current flows as shown by the ammeter. The plate current will rise and fall because the voltage on the plate is rising and falling. Current in a given circuit is directly proportional to voltage. During the second half-cycle period, the plate's polarity will be negative. Under this condition, for this entire period, the diode will not conduct. If the ammeter could respond rapidly, it would drop to zero. The plate-current waveform (I_p) in figure 1-5 shows zero current during this period.

The effects of applying alternating voltage to the plate of the diode are the following. Diode plate current flows during the positive half-cycle. It changes value as the plate voltage rises and falls. The diode cuts off plate current during the entire period of the negative half-cycle. Diode plate current flows in pulses because the diode cuts off half the time. Diode plate current can flow in only one direction. It is always dc (in this case pulsating dc-one that flows in pulses). In effect, the diode has caused an alternating voltage to produce a direct current.

The ability to obtain direct current from an ac source is very important and one function of a diode that will be seen again and again in electronics work.

The circuits discussed up to this point were chosen to show the general concepts discovered by Edison and Fleming. They are not practical because they do no useful work. For now, only the concepts are important. Practical circuitry will be presented later in this lesson along with specific points about the construction, limitations, and other characteristics of modern diode tubes.

Construction of Diode Tube

Diode tubes presently in use are descendants of Fleming's valve. There is a family resemblance, but many changes have been made from the original. Diodes are both smaller and larger, less powerful and more powerful, and above all, more efficient and more reliable. The search for greater efficiency and reliability has resulted in many physical changes.

Filaments. Modern filaments in all tubes last longer and emit greater amounts of electrons for a given size. Many operate at a lower temperature than in the early days. Most improvements have resulted from the use of new materials and from better quality control during manufacture.

Three materials that are commonly used as filaments are tungsten, thoriated tungsten, and oside-coated metals.

Tungsten has great durability but requires large amounts of power for efficient thermionic emission. Thoriated-tungsten filaments are made of tungsten with a very thin coat of thorium, which is a much better emitter of electrons than tungsten alone. Oxide-coated filaments are made of metal, such as nickel, coated with a mixture of barium and strontium oxides. The oxide coat, in turn, is coated with a one-molecule-thick layer of metal barium and strontium.

Oxide coating produces great emission efficiency and long life at relatively low-heat levels.

A major advance in electronics was the elimination of batteries as power sources for tubes. Except in electronic devices designed to be operated away from the power source, alternating current is used to heat filaments.

A separate filament transformer may supply voltage or it may be taken from a filament winding that is part of a power transformer. The actual voltage may vary from 1 volt up and is dependent on the design of the tube. Common filament voltages are 5.0, 6.3, and 12.6 volts of ac. Filaments may be connected in series with other tube filaments or may be in parallel with each other. This is determined by the equipment designer.

Cathodes. As was mentioned previously, a more formal name for the electron-emitting element in a tube is the cathode. Cathodes in all tubes, not just diodes, are of two general types: either directly heated or indirectly heated. Each type has its advantages and disadvantages.

Directly Heated Cathodes. In all the discussions so far in this lesson, the filament that has been the electron emitted is the directly heated type of cathode. Directly heated cathodes are fairly efficient and are capable of emitting large amounts of electrons. Figure 1-6 shows this type of cathode and its schematic symbol. An added advantage of this type of filament is the rapidity with which it reaches electron-emitting temperature. Because this is almost instantaneous, many pieces of electronic equipment that are turned on at infrequent intervals and must be usable instantly have directly heated cathode tubes.

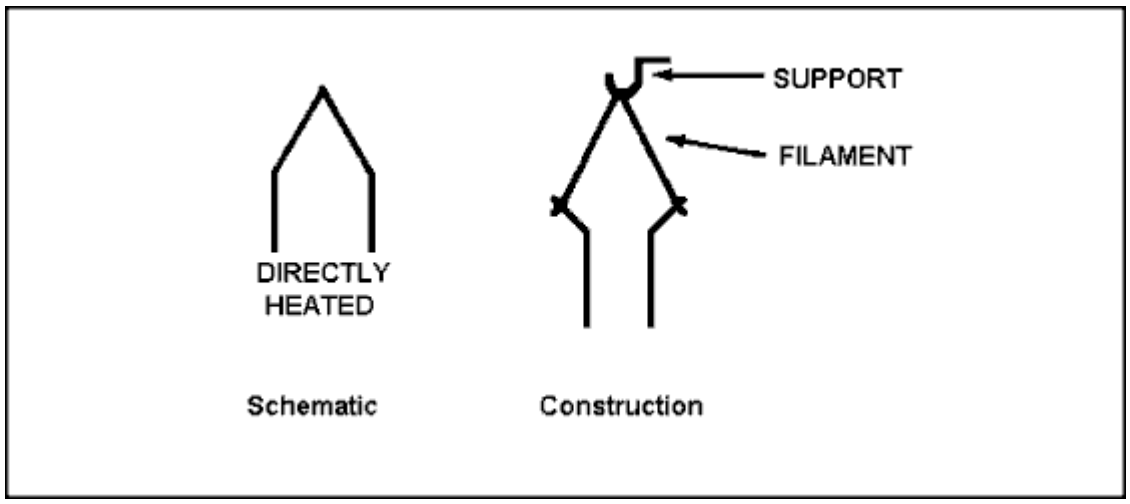


Figure 1-6. Directly Heated Cathode Schematic Representation.

Because of its construction, parts of the filament are closer to the plate than other parts. This results in unequal emission and a loss of efficiency. Another disadvantage occurs when dc is used to heat a filament. The filament represents a resistance. When current flows through this resistance, a voltage drop occurs. The result is that one side of the resistance, or filament, is more negative than the other side. The negative side of the filament will emit more electrons than the positive side, which, again, is less efficient than if the filament has equal emission across its entire surface.

When ac is the source of filament power, it causes a small increase and decrease of temperature as it rises and falls. In turn, this causes a small increase and decrease of emitted electrons. This effect is not too important in many diode circuits and is undesirable in other tube circuits.

Indirectly Heated Cathodes. Figure 1-7 shows this type of cathode and its schematic symbol. Indirectly heated cathodes are always composed of oxidecoated material. The cathode is a cylinder, a kind of sleeve, that encloses the twisted-wire filament. The only function of the filament is to heat the cathode. The filament is often called a heater when used in this manner.

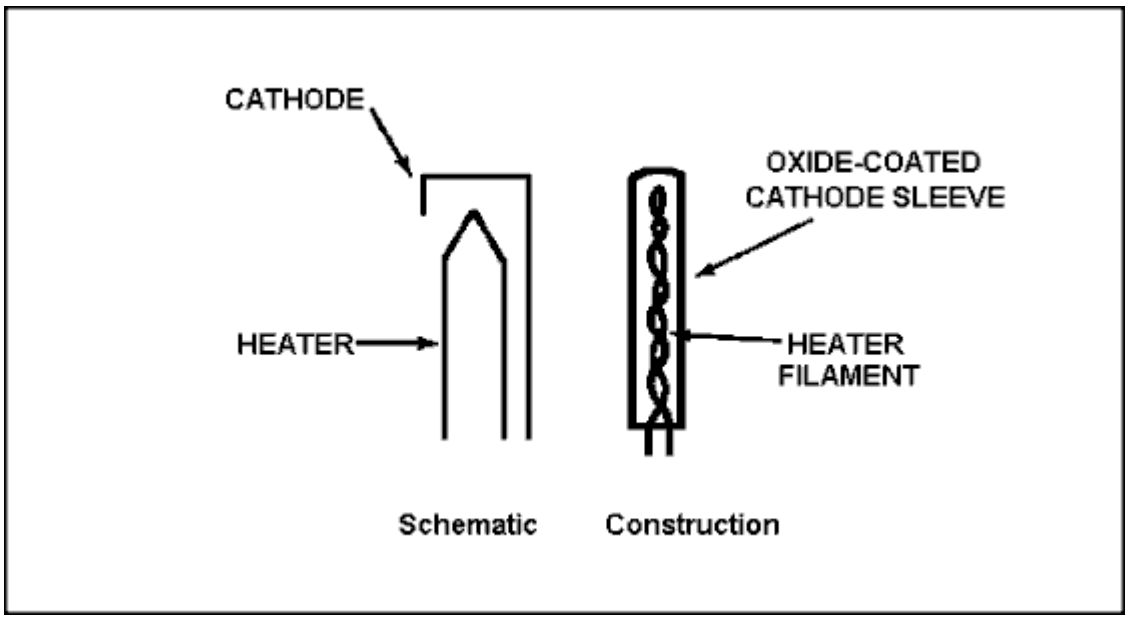


Figure 1-7. Indirectly Heated Cathode Schematic.

Some schematics do not show heaters and heater connections. Heaters, of course, are still present in the tubes, but their appearance in a schematic adds little to understanding the circuit. The heater is not considered to be an active element. For example, a tube with an indirectly heated cathode and a plate is still called a diode even though it might seem that there are three elements in the tube.

Because indirectly heated cathodes are relatively large, they take longer to heat to electron-emitting temperature. Once up to the necessary temperature, however, they do not respond to the small variations in heater temperature caused by ac fluctuations. Because of the inherent advantages, most tubes in use today have indirectly heated cathodes.

Plates. Edison's plate was a flat piece of metal. Plates are no longer flat, but are designed in many different shapes. Figure 1-8 shows two diodes, one with a directly heated cathode and the other with an indirectly heated cathode. Each plate is cut away to show the internal position of elements and the plate shapes.

Plates must be able to hold up under the stress of heat created by the flow of plate currents and the closeness of hot cathodes. They need to be strong enough to withstand mechanical shocks produced by vibration and handling. Some typical materials used for electron-tube plates are tungsten, molybdenum, graphite, nickel, tantalum, and copper.

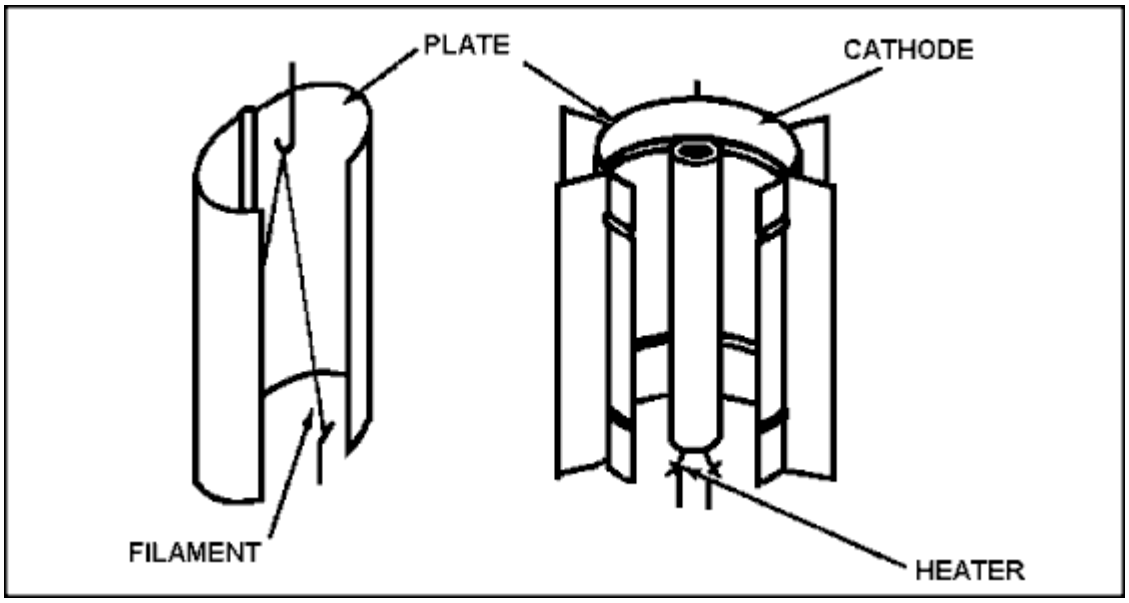


Figure 1-8. Cutaway View of Plate Cathode Construction.

Tube Bases. Figure 1-9 shows the construction of a diode. The base shown has two functions. First, it serves as the mounting for tube elements. Second, it serves as the terminal points for the electrical connections to the tube elements. This is accomplished by molding or otherwise bringing pins (or prongs) through the base. The internal ends of these pins are connected to tube elements. The base must be mechanically strong and made of an insulating material to prevent the tube elements from shorting.

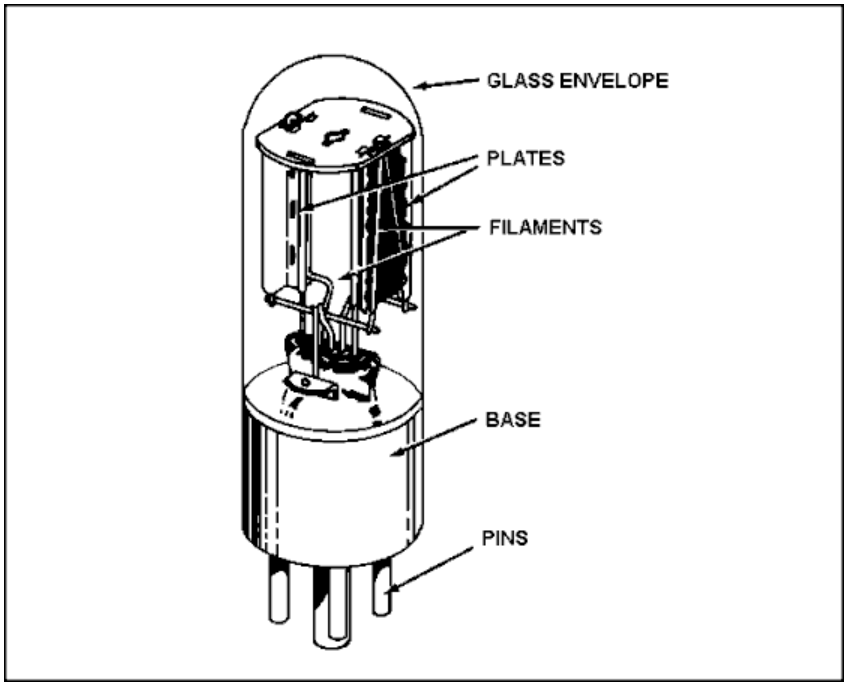


Figure 1-9. Diode Construction.

Tube Sockets and Pin Numbering. Because they require relatively frequent replacement, most tubes are designed to plug into sockets permanently mounted in the equipment. Tube pins and sockets are designed so that tubes cannot be plugged in incorrectly. Tube sockets must make secure mechanical and electrical contact with tube pins, must insulate pins from each other, and must provide terminals to which circuit components and conductors are connected.

Each element of a tube is connected to a pin in its base. To trace a circuit easily and efficiently, it will be necessary for you to match elements with their pin numbers. This information is available in tube manuals and equipment schematics. Figure 1-10 shows these numbers on one example of a diode symbol. Note also the designation V1 beside the tube. Electron tubes are often identified in schematic diagrams by V and a number.

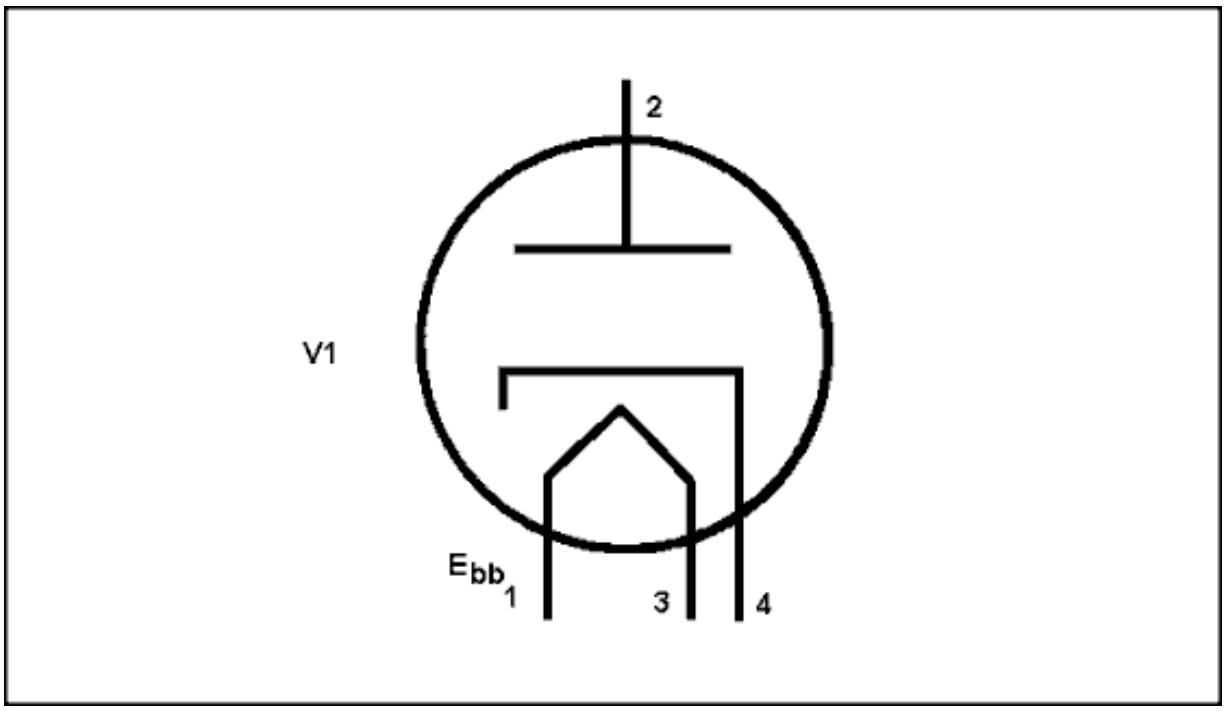


Figure 1-10. Identification of Tube Elements.

Figure 1-11 shows five common pin configurations as viewed from the bottom of each tube or socket. This is important. In every case, pins and pin connections on sockets are numbered in a clockwise direction when viewed from the bottom. In each of the five pictures in figure 1-11, there is an easily identified point from which to start numbering. In the four-prong and six-prong tubes, the point is between the two larger prongs. In the octal tube, the point is directly down from the keyway in the center of the tube. In the seven-pin and nine-pin miniatures, the point is identified by the larger distances between pins.

Envelope. The envelope of a tube may be ceramic, metal, or glass. Its major purpose is to keep the vacuum in and the atmosphere out since the heated filament would burn up in the atmosphere. There are other reasons for providing a vacuum, but the important thing is to realize that a tube with a leaky envelope will not function properly.

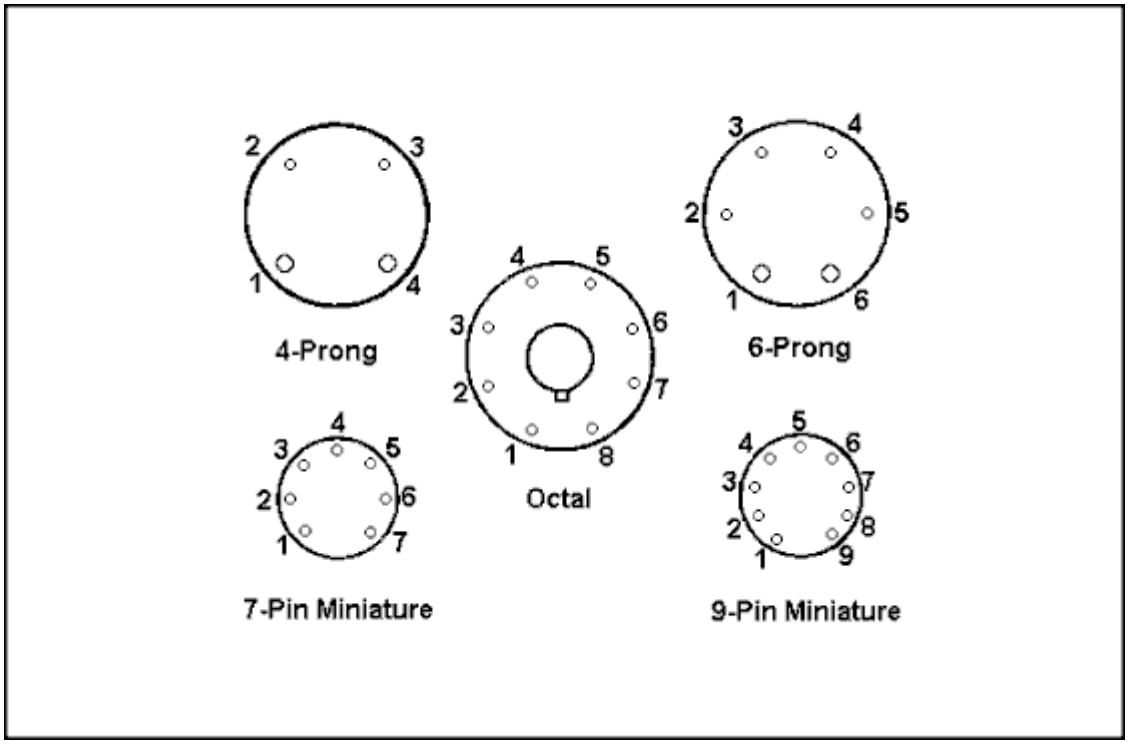


Figure 1-11. Pin Identification (All Tubes Are Viewed From the Bottom).

The silver spot sometimes seen on the inside surface of the glass envelope of a vacuum tube is normal. It is caused by the "flashing" of a chemical during the manufacture of the tube. Burning the chemical, called the getter, helps to produce a better vacuum and eliminates any remaining gases.

Electrical Parameters of Diodes

Thousands of different tubes exist. While many of them are similar and even interchangeable, many have unique characteristics. It is a fact that differences in materials, dimensions, and other physical characteristics result in differing electrical characteristics.

The electrical parameters of a diode, and any tube, are specific characteristictics and limitations. In the process of discussing parameters, we will be working with exact values. Voltages will be increased and decreased and the effects measured. Limiting factors and quantities will be explored and defined. The discussion will be based on simplified and experimental circuits.

Practically all of the parameters, limitations, definitions, and abbreviations that will be covered in these next paragraphs will be directly applicable to the more complex tubes and circuits you will study later in this lesson. Diode parameters are the foundation for all that follows.

Symbols. You have learned to use letters and letter combinations to abbreviate or symbolize electrical quantities. (The letters E, I, and R are examples.) This practice will be continued in references to tube quantities. Be aware that other publications may use different abbreviations. Many attempts have been made to standardize such abbreviations, but none has succeeded completely.

Table 1-1 lists electron-tube symbols used in the remainder of this subcourse. The right-hand column shows equivalent symbols that you may find in other texts and courses.

Table 1-1. Symbols for Tube Parameters.

Symbols This Text	*Meaning*	*Other Texts*
E_p	PLATE VOLTAGE, DC VALUE	
E_{bb}	PLATE SUPPLY VOLTAGE, DC	B+
E_c	GRID BIAS VOLTAGE, DC VALUE	E_g
E_{cc}	GRID BIAS SUPPLY VOLTAGE, DC	C–
e_p	INSTANTANEOUS PLATE VOLTAGE	
e_c	INSTANTANEOUS GRID VOLTAGE	
e_g	AC COMPONENT OF GRID VOLTAGE	
e_p	AC COMPONENT OF PLATE VOLTAGE (ANODE)	
I_p	DC PLATE CURRENT	
R_p	DC PLATE RESISTANCE	
R_g	GRID RESISTANCE	
R_k	CATHODE RESISTANCE	
R_L	LOAD RESISTANCE	

Plate Voltage-Plate Current Characteristic. A positive voltage on the diode plate allows current to flow in the plate circuit. Each diode, depending on the physical and electrical characteristics designed into the diode, is able to pass an exact amount of current for each specific plate voltage (more voltage equals more current--at least to a point). The plate voltage-plate current characteristic for a given diode is a measure of exactly how much plate voltage controls how much plate current. This is often called the E_p-I_p characteristic. The E_p-I_p characteristic for a given diode is determined by design engineering using mathematical analysis and laboratory experiment.

Assume that we have the circuit in figure 1-12. (The filament has proper voltage even though it isn't shown on the diagram.) Our purpose is to determine just how a changing voltage on the plate changes (or controls) the plate current.

Starting with zero volts from the variable dc voltage source, increase the plate voltage (E_p) in steps of 50 volts until 400 volts are reached. At each 50-volt step, measure the milliamperes of plate current (I_p) that flow through the meter. Record the I_p meter readings, step by step, so that the results may be analyzed.

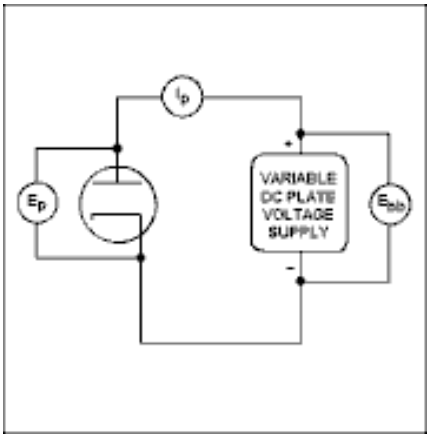


Figure 1-12. Determining Diode Plate Characteristics.

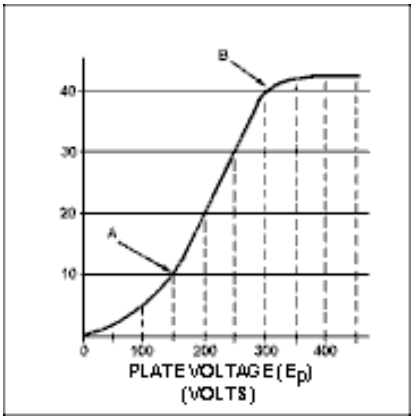


Figure 1-13. E_p ***-I_p Characteristic Curve.***

Assume that table 1-2 shows the results. While the table could be used, a more normal procedure is to plot a graph of the values. Such a graph is called an E_p-I_p curve and is shown in figure 1-13. Each tube has its own E_p-Ip curve, which is available in commercial tube manuals and in many equipment technical manuals. Each curve will be different in some respects from every other curve. The shapes, however, will be similar.

Table 1-2. E_p -Ip Values Obtained by Experiment.

E_p	0	50	100	150	200	250	300	350	400
I_p	0	.002	.005	.010	.020	.030	.040	.042	.045

The E_p-I_p curve in figure 1-13, although just an example, is typical of real plate characteristic curves. Certain characteristics applicable to diodes and other tubes may be learned by studying it. First, look at the part of the curve to the left of point A. Because it is not a straight line, it is referred to as nonlinear. Notice that a change of 150 volts (0-150) causes a change to 10mA of plate current (0-10). In comparison with the straight-line part of the curve, between points A and B, this is a relatively small change in current. The smaller the change in current, the flatter the curve.

An explanation of this nonlinear portion of the curve follows. The electron emitted by a cathode forms a cloud around the cathode. This cloud is called the space charge. The closer the space charge is to the cathode, the more densely packed it is with electrons. In the example, the lower plate voltages (0-150 volts) over this part of the curve exert a pull on only the outer fringe of the space charge where there are few electrons. This results in relatively few electrons flowing to the plate.

The center portion of the curve between A and B is known as the linear portion because it is nearly a straight line. Over this portion, a change of 50 volts E_p causes a change of 10 mA I_p.

The reason for the increased change in plate current for a given change of plate voltage also has to do with the space charge. With a higher plate voltage (over 150 volts), the attraction from the plate begins to influence the denser part of the space charge that has greater numbers of electrons. Therefore, a higher current flows for a given voltage than in the nonlinear part. The curve becomes steeper. In the example, this linearity continues to about 300 volts, point B.

The plate current plotted at the top portion of the curve is produced by the higher plate voltages. However, the amount of current change for a given voltage change is greatly reduced. The reason for this again involves the space charge. At about 300 volts, almost all of the electrons in the space charge are flowing to the plate. A higher voltage cannot attract more electrons because the cathode cannot produce any more. The point where all (or almost all) available electrons are being drawn to the plate is called plate saturation or simply saturation. It is one of the limiting factors of every tube. The most consistent control of plate current takes place over the linear portion of the E_p-I_p curve. In most applications, electron tubes are operated in this linear portion of the characteristic curve.

Plate Resistance (Rp). One tube parameter that can be calculated from values on the E_p-I_p curve is known as plate resistance, abbreviated R_p. In a properly designed electron tube, there is no physical resistor between cathode and plate, that is, the electrons do not pass through a resistor in arriving at the plate. There is, however, a very effective resistance between cathode and plate. It is not lumped in a resistor, but the circuit may be analyzed as if it were. The plate resistance of a given tube, R_p, can be calculated by applying Ohm's law to the values of E_p and I_p. Figure 1-14 is a typical diode E_p-I_p curve. The plate resistance is figured for R_p under three different conditions. These are figured as follows:

Given (for example):

E_p = 20 volts
I_p = 40 milliamperes
1 mA = .001 ampere; therefore, 40 mA = .040 ampere

Solution:

$$R_p = \frac{E_p}{I_p}$$

$$R_p = \frac{20 \text{ volts}}{.040 \text{ ampere}}$$

$$R_p = 500 \text{ ohms}$$

The other two indicated values of R_p are figured in the same way. There is very little difference in plate resistance when the E_p and Ip values are taken from the linear portions of curves. Rp is the effective resistance offered to dc.

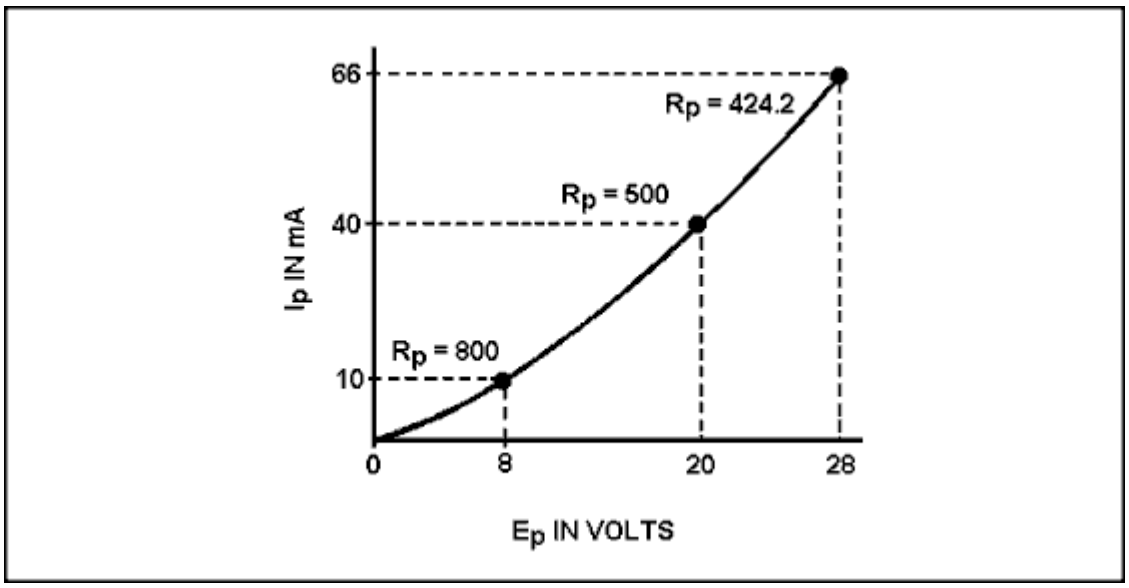


Figure 1-14. E_p -Ip Characteristic Curve for a Diode.

Gas diodes are of a type of tube that has not yet been discussed. They are mentioned here only because of their plate resistance characteristic. Instead of a high-vacuum environment, some tubes have small amounts of gas introduced in the envelope vacuum during manufacture. Argon, neon, helium, or mercury vapor are commonly used.

When a certain minimum voltage is placed on the plate, the gas molecules in the envelope ionize. This happens by a process that will be explained when gas diodes are studied. The positive ions tend to cancel some of the effects of the space charge that influence plate resistance in a vacuum tube. This canceling reduces internal plate resistance to a relatively low, constant value. In applications that require a large plate current, the low-plate resistance of a gas-filled diode has an efficiency that cannot be approached by a high-vacuum diode.

Plate Dissipation. When electrons are attracted from the space charge to the plate, they are accelerated by the attraction. This speed gives them energy that causes the plate to be struck with considerable force. As the electrons strike the plate, this energy is converted to heat. The plate must be able to withstand the increase in temperature. The maximum amount of power (watts) that a given plate can safely dissipate is called the plate dissipation rating. The amount of plate dissipation for a given tube under a particular set of plate conditions may be found by applying the following equation:

Plate dissipation =Ep x Ip
= 20 volts x .040 ampere
= .8 watt

This is a relatively small wattage. It's probable that the plate of the example diode is not overheating. (Refer to a tube manual for further explanation.) Plate dissipation is a circuit that must be made good by the power source in a circuit. In the above example, this is the plate voltage supply.

Peak Current Rating. The maximum instantaneous current that a tube can pass in the normal direction (cathode to plate) without damage is called the peak current rating. Peak current rating is determined by the amount of electrons available from the cathode and the length of time plate current flows.

Peak Voltage Rating. This is the maximum instantaneous voltage that can be applied to a tube in the normal direction without a breakdown.

Peak Inverse Voltage (PIV) Rating. This is the maximum voltage that can be applied to a tube in the reverse direction (plate negative with respect to cathode). Exceeding this will cause arc-over from plate to cathode and will damage the tube. PIV becomes very important in the rectifier circuit.

Transit Time

Occurrences in electricity and electronics are often explained as if they happen instantaneously. As fast as electricity acts, however, it takes time between cause and effect. Each tube has a factor called transit time, which is the time it takes for an individual electron to move from cathode to plate. In certain applications involving high-frequency voltages, transit time places a limitation on tubes. This limitation will be explained when the circuits affected by it are discussed.

TRIODE TUBE

Diode electron tubes can be used as rectifiers and switches as well as in many other ways. They are still used in Fleming's original application in radio circuits. The diode can be seen in just about every piece of electronic equipment.

Construction of Triode Tube

As with all inventions, Fleming's diode was immediately the subject of much experimentation and many attempts at improvement. An American experimenter, Dr. Lee DeForest, added another active element to the diode in 1906. He was trying to improve the radio application of Fleming's diode. His new tube was eventually called a triode. DeForest's triode was not very successful as a radio detector. More importantly, in 1912, DeForest discovered that his original triode could amplify or magnify very weak electrical impulses.

It is because of the triode's ability to amplify that DeForest is honored as one of the great radio pioneers.

The immediate application of the triode amplifier was in telephone and radio. Both fields were limited because electrical impulse signals became weaker and weaker as the distance from the signal source increased. The triode, along with other developments of the time, made long-distance communications possible. The amplifying tube was the real beginning of modern electronics and influenced everything that followed.

A type of amplification is step-up transformers, which are discussed in FM 11-61 (Communications-Electronics Fundamentals: Basic Principles of Alternating Current). An input voltage applied to the primary of a step-up transformer is increased in amplitude at the secondary by a factor determined by the step-up turns ratio. For example, if 5 volts are applied to the primary of a 1:3 set-up transformer, the secondary would produce 15 volts. In other words, the input voltage is amplified by a factor of 3. When applied to electronic circuits, these primary and secondary voltages are more often called signals, or input signal and output signal, respectively. In electronics it is sometimes necessary to increase the amplitude of an input signal many times. Because of size and design limitations, transformers are usually not practical for use in electronics as amplifiers.

DeForest's first experiment with the diode was to place an additional metal plate between the cathode and plate. An ac signal was applied to this piece of metal between the cathode and the plate. When the circuit was energized, DeForest found that the ammeter stayed on zero regardless of the polarity of the input signal. What was happening was that the new element was blocking (or shadowing) the plate. Any electrons attempting to reach the plate from the cathode would hit the new element instead. Since the circuit didn't work, further experimentation was necessary.

In his next attempt, DeForest decided to change the element between the cathode and plate. Instead of a solid metal plate, he used a wire mesh. In this way electrons could flow from the cathode, through the wire mesh, to the plate. This tube circuit is shown in figure 1-15. View A shows DeForest's circuit with 0 volts applied to the third element (today called a control grid or, occasionally, just the grid). Under these conditions, assume that the ammeter reads 5 milliamperes. With no voltage applied to the grid, the grid has little effect on the electron stream. For all practical purposes, the control grid is not there. Most electrons flow through the open mesh. The tube functions as a diode.

View B shows DeForest's tube with +3 volts applied to the control grid. When DeForest applied this voltage, he found that plate current, Ip, increased by a large amount (doubled). The only way to double the plate current in a diode is to increase the plate voltage by a large amount. Yet, DeForest had doubled plate current by applying only 3 volts positive to the control grid.

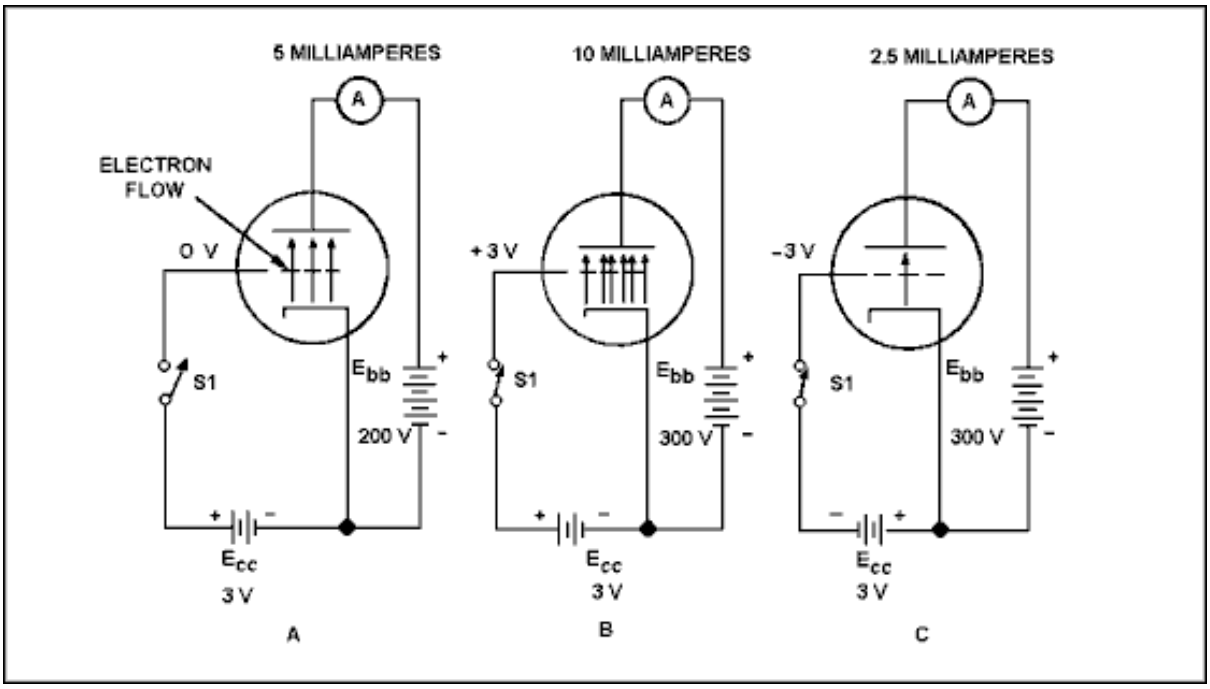


Figure 1-15. DeForest's Experiment.

The reason for this is that when the control grid was made positive, electrons surrounding the cathode (negative charges) were attracted to the grid. Since the grid is a metal mesh, most of the electrons, instead of striking the grid wires, were propelled through the holes in the mesh. Once they had passed the grid, they were attracted to the positive charge in the plate.

The study of capacitors shows that opposites attract because of electrostatic lines of force, and the strength of electrostatic lines of force decreases with distance. In DeForest's tube, the grid was placed very close to the cathode. Therefore, it had a greater effect on current flow from the cathode than the plate that was placed at a much greater distance from the cathode. For this reason DeForest was able to double the current flow through the tube with only +3 volts applied to the grid.

DeForest had certainly made a discovery. Now the problem was to find out what happened when a negative potential was applied to the grid. This is shown in view C of figure 1-15. When DeForest applied -3 volts to the grid, he found that plate current was decreased to half of what it was when the grid had no voltage applied to it. The reason for this is found in the principle of "likes repel." The negatively charged grid simply repelled some of the electrons back toward the cathode. In this manner, the attractive effect of the plate was decreased, and less current flowed to the plate.

DeForest, using his new tube (which he called a triode because it had three elements in it), was able to control relatively large changes of current with very small voltages. In DeForest's circuit, the small input signal was ±3 volts

dc. What DeForest got for an output was a variation in plate current of 7.5 milliamperes. Instead of amplification, DeForest had obtained "conversion," or in other words, had converted a signal voltage to a current variation. This wasn't exactly what he had in mind. As it stood, the circuit wasn't very useful. Obviously, something was needed. After examining the circuit, the answer became obvious--Ohm's law. DeForest wanted a voltage change, not a current change. The answer was simple.

If you want	E	and you have	I	simply add	R

(E = I x R)

In other words, run the plate current variation (caused by the voltage on the grid) through a resistor and cause a varying voltage drop across the resistor. This is shown in figure 1-16.

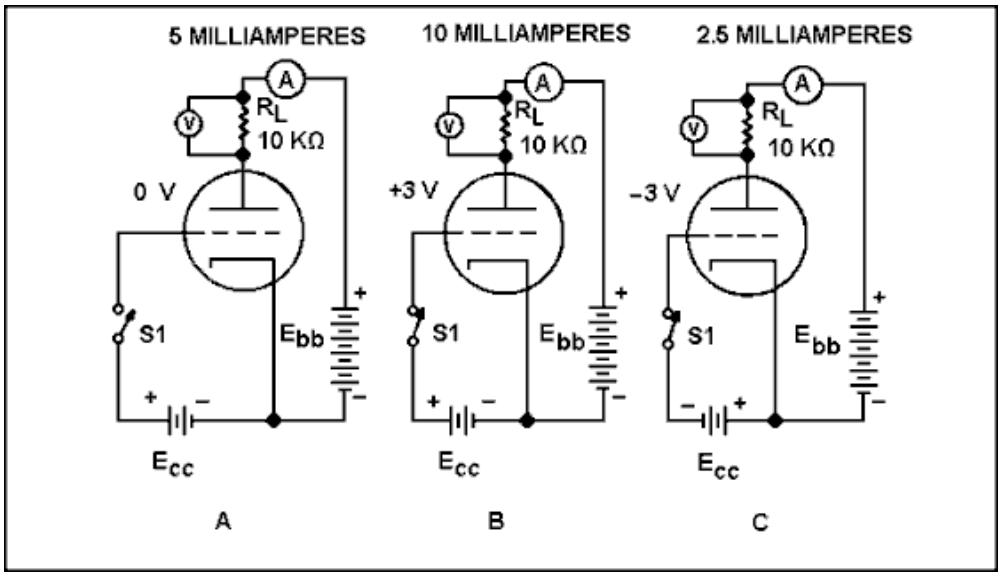


Figure 1-16. Operation of the Plate-load Resistor.

The circuit is identical to the one in figure 1-15 except that now a resistor (called a plate-load resistor, R_L) has been added to the plate circuit, and a voltmeter has been added to measure the voltage drop across R_L.

In view A of figure 1-16, the control grid is at 0 volts. Once again 5 milliamperes flow in the plate circuit. The 5 milliamperes must flow next through R_L. The voltage drop is equal to:

E = I x R
E = (5×10^{-3} amperes) X (10×10^{3} ohms)
E = .(5×10^{-3}) X (10×10^{-3})
E = 5 x 10
E = 50 volts

Thus the voltage drop across the plate-load resistor, R_L, is 50 volts when no voltage is applied to the grid. In view B of the figure, +3 volts are applied to the control grid. Once again, plate current increases to 10 milliamperes. The voltage drop across R_L is:

$E = I \times R$
$E = (10 \times 10^{-3} \text{ amperes}) \times (10 \times 10^{3} \text{ ohms})$
$E = 10 \times 10$
$E = 100 \text{ volts}$

By applying +3 volts to the grid, the voltage drop across RL is increased by 50 volts (from the original 50 volts to 100 volts). In view C, -3 volts have again been applied to the control grid. Plate current decreases to 2.5 milliamperes, and the voltage drop across R_L drops to 25 volts.

The voltage across R_L has become varied by varying the grid voltage. The grid voltage, or input signal, varies from +3 to -3 volts or 6 volts. The voltage drop across R_L varies from 25 volts to 100 volts, or 75 volts. In other words, the triode has caused a 6-volt input signal (varying) to be outputted as a signal that varies by 75 volts. This is known as amplification.

In figure 1-15 the positive charge on the grid causes more plate current to flow. However, when the grid becomes positive, it begins to act as if it is a small plate. It draws a few electrons from the space charge. These electrons flow from the cathode across the gap to the positive grid and back through the external grid circuit to the cathode. This flow is known as grid current. In some tube applications, grid current is desired. In others it is relatively harmless. In some, grid current causes problems and must be eliminated.

Most amplifier circuits are designed to operate the grid negative relative to the cathode. The voltage that causes this is called a bias voltage. The symbol for the bias supply is E_{CC}. One effect of bias (there are several other very important ones) is to reduce or eliminate grid current.

Grid bias is a steady, direct voltage that is placed at some point in the external circuit between the grid and cathode. It may be in the cathode leg or the grid leg as shown in figure 1-17. It is always in series with the input signal voltage. In each of the circuits in figure 1-17, E_{CC} makes the grid negative

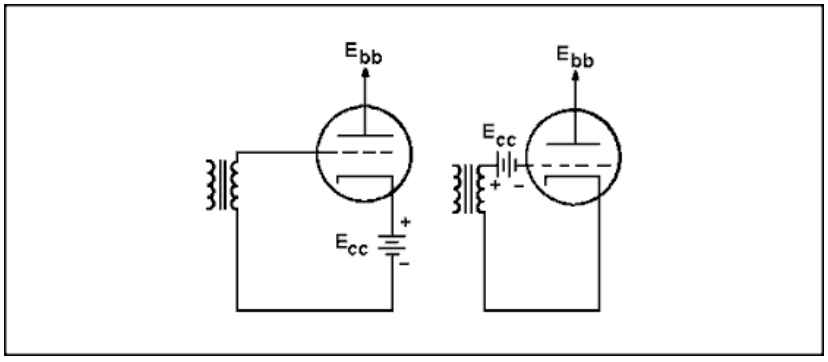
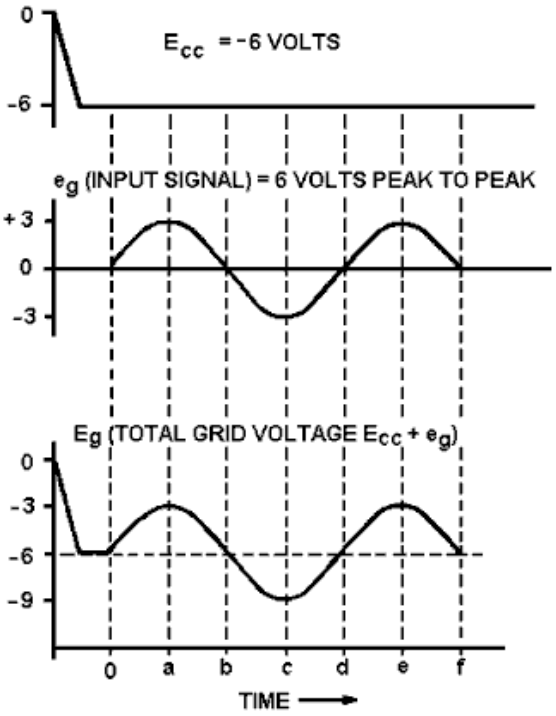


Figure 1-17. Basic Biasing of a Triode.

with respect to the cathode because of the negative terminal's being connected toward the grid and the positive terminal's being connected toward the cathode. With identical components, each circuit would provide the same bias.

Battery bias is practically never used in modern circuits. Because of its simplicity, however, it is used in analyzing the effects of bias.

Assume that the bias voltage in figure 1-17 is -6 volts. Also, assume that the peak-to-peak signal voltage from the transformer is 6 volts. Each of these voltage waveforms is shown in figure 1-18. Voltages in series add. Figure 1-18 has a table of the instantaneous values of the two voltages added together. The waveforms are drawn from these values.



Time	*0*	*a*	*b*	*c*	*d*	*e*	*f*
Bias (E_c)	-6	-6	-6	-6	-6	-6	-6
Signal (e_g)	0	+3	0	-3	0	+3	0
Total Grid Volts (E_g)	-6	-3	-6	-9	-6	-3	-6

Figure 1-18. Typical Grid Waveforms.

Because the bias voltage is more negative than the signal voltage is positive, the resultant voltage (bias plus signal), E_g, is always negative. The signal, in this case, makes the grid voltage go either more or less negative, (-9 to -3), but cannot drive it positive. Under these circumstances, the negative grid always repels electrons from the space charge. The grid cannot draw current. Any problems associated with grid current are eliminated, because grid current cannot flow to a negative grid.

Negative bias also reduces plate current flow. It is for the circuit designer to choose a bias and an input signal that, when added together, neither allows the grid to become positive nor to become negative enough to stop plate current.

Operation of Triode Tube

The circuit in figure 1-19 brings together all of the essential components of a triode amplifier. Before analyzing the circuit, however, the term quiescent needs to be defined. Quiescent identifies the condition of a circuit with no input signal applied. With a given tube, bias supply, and plate supply, an exact amount of plate current will flow with no signal on the grid. This is known as the quiescent value of plate current. The quiescent value of plate voltage is the voltage between cathode and plate when quiescent current flows. Simply stated, quiescent describes circuit conditions when the tube is not amplifying. The tube has no output signal and is in a standby, waiting condition.

Refer to figure 1-19. With no input signal, under quiescent conditions, assume that 1 milliampere of current flows through the tube, cathode to plate. This current (I_p) will flow through R_L (load resistor) to the positive terminal of the battery. The current flowing through R_L causes a voltage drop (IR) across R_L equal to:

$E = I_p \times R_L$
$E = 1 \times 10^{-3}$ amperes $\times$ 100 $\times 10^3$ ohms
$E = 100$ volts

Subtracting the voltage dropped across the plate-load resistor from the source voltage of 300 volts gives you 200 volts (300 volts - 100 volts). Thus, the plate voltage (E_p) is at 200 volts. The quiescent conditions for the circuit are:

grid voltage = -6 volts
plate voltage (E_p) = +200 volts

These values are shown on the waveforms as time a in figure 1-19. Note that even though the grid is more negative (-6 volts) than the cathode, the tube in the circuit is still conducting, but not as heavily as it would if the grid were at zero volts.

Now look at the input signal from the transformer secondary. For ease of explanation, only three points of the ac sine wave input will be considered: point b, the maximum negative excursion; point c, the maximum positive excursion;

and point d, the zero reference or null point of the signal. At time b, the input signal at the grid will be at its most negative value (-3 volts). This will cause the grid to go to -9 volts (-6 volts + -3 volts). This is shown at time b on the grid voltage waveform. The increased negative voltage on the control grid will decrease the electrostatic attraction between the plate and cathode. Conduction through the tube (Ip) will decrease. Assume that it drops to .5 milliampere. The decrease in plate current will cause the voltage drop across the plate-load resistor (RL) to also decrease from 100 volts, as explained by Ohm's law:

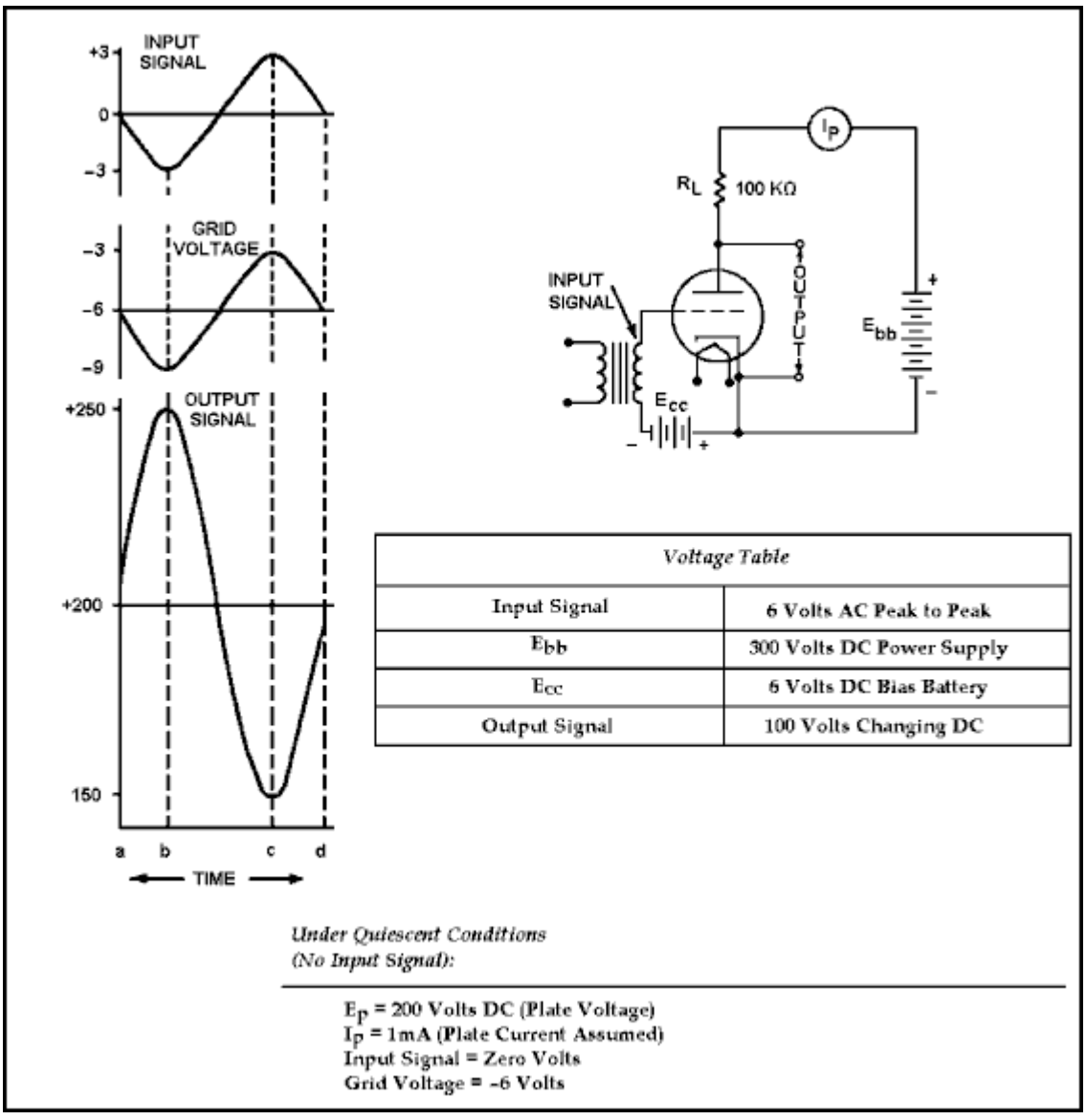


Figure 1-19. Triode Operation.

$E = I_p \times R_L$
$E = .0005$ ampere x 100,000 ohms

Or

$E = (.5 \times 10^{-3}$ amperes) x (100×10^3 ohms)
$E = 50$ volts
Plate voltage will then rise to +250 volts.
$E_p = 300$ volts - 50 volts = 250 volts

This is shown on the output signal waveform at time b.

At time c the input has reached its maximum positive value of +3 volts. This will decrease grid voltage to -3 volts (-6 volts +3 volts). This is shown on the grid voltage waveform at time c. This, in turn, will increase the electrostatic force between the plate and cathode. More electrons will then flow from the cathode, through the grid, to the plate. Assume that the plate current in this case will increase to 1.5 milliamperes. This will cause plate voltage (E_b) to decrease to 150 volts as shown below.

$E = I_p \times R_L$
$E = (1.5 \times 10^{-3}$ amperes) x (100×10^3 Ohms)
$E = 150$ volts
$E_p = 300$ volts - 150 volts
$E_p = 150$ volts

This is shown on the output waveform at time c. At time d the input signal voltage decreases to zero volts. The grid will return to the quiescent state of -6 volts, and conduction through the tube will again be at 1 milliampere. The plate will return to its quiescent voltage of +200 volts (shown at time d on the output waveform).

Varying the grid by only 6 volts has caused the output of the triode to vary by 100 volts. The input signal voltage has been amplified (or increased) by a factor of 16.6. This factor is an expression of amplifier voltage gain and is calculated by dividing the output signal voltage by the input signal voltage.

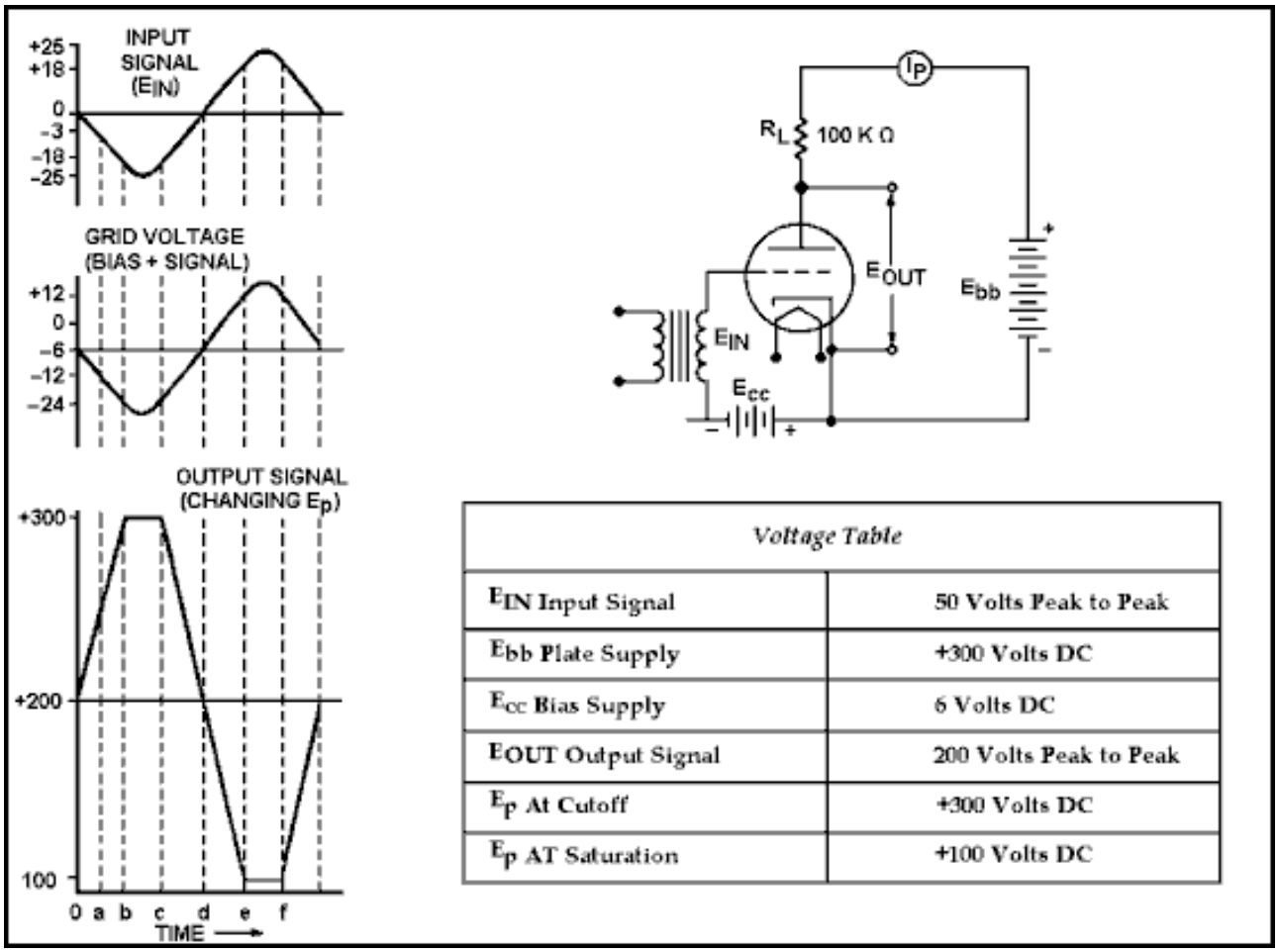
In the waveforms in figure 1-19, note that the output voltage of the amplifier is 180° out of phase with the input voltage. This polarity inversion is a characteristic of any amplifier in which the input is placed on the control grid and the output is taken between the cathode and plate. This is normal and should not confuse you when you troubleshoot or work with this type of circuit.

The triode circuit just discussed is simple. In actual application, triode circuits are more complex. There are two reasons for this. The first has to do with the triode's ability to amplify and perform other functions. Triodes come in many different types. Each of these types has different internal characteristics and different capabilities. Because of this, each triode circuit must be designed to accommodate the triode's special characteristics.

The second reason for the increase in complexity of triode circuits has to do with distortion. Distortion occurs in a tube circuit any time the output waveform is not a faithful reproduction of the input waveform. Polarity inversion and voltage gain of the output waveform are not considered to be included in this definition of distortion. Some circuits are designed to distort the output. The reason and methods for this deliberate distortion will be presented later. In most cases, however, circuits are designed to eliminate or reduce distortion.

Because the grid is close to the cathode, small changes in grid voltage have large effects on the conduction of triodes. If a large enough input signal is placed on the grid, a triode may be given into either plate-current cutoff or plate-current saturation. When this occurs, the tube is said to be overdriven. Overdriving is considered to be a form of distortion.

Note time zero in the waveforms in figure 1-20. The input signal (E_{IN}) is at zero volts. Grid voltage equals the bias voltage (-6 volts), and 1 milliampere of current is flowing through the tube (quiescent state). Plate voltage (E_p) is 200 volts.



Voltage Table	
E_{IN} Input Signal	50 Volts Peak to Peak
E_{bb} Plate Supply	+300 Volts DC
E_{cc} Bias Supply	6 Volts DC
E_{OUT} Output Signal	200 Volts Peak to Peak
E_p At Cutoff	+300 Volts DC
E_p AT Saturation	+100 Volts DC

Figure 1-20. Overdriven Triode.

On the negative half of the input signal, the grid voltage is made more negative. This reduces plate current that, in turn, reduces the voltage drop across R_L. The voltage between cathode and plate is thereby increased. These relationships can be seen by following time a through the three waveforms.

Let's make the assumption that this particular triode cuts plate current flow off when the grid reaches -24 volts. This point is reached at time b when E_{IN} is -18 and the bias is -6 (-18 and -6 = -24). Plate current remains cut off for as long as the grid is -24 volts or greater.

With zero current flowing in the plate circuit, there is no voltage drop across R_L. The entire plate supply voltage, E_{bb} (300 volts), appears at plate voltage between cathode and plate. This is shown at time b in the output signal waveform. Between times b and c, the grid voltage is greater than -24 volts. The plate current remains cut off, and the plate voltage remains at +300. The output waveform between times b and c cannot follow the input because the plate voltage cannot increase above +300 volts. The output waveform is "flattopped." This condition is known as amplitude distortion.

When the grid voltage becomes less negative than -24 volts, after time c the tube starts conducting and the circuit again produces an output.

Between times c and d, the circuit continues to operate without distortion. At time e, however, the output waveform is again distorted and remains distorted until time f.

Every cathode is able to emit a certain number of electrons. When that maximum number is being emitted, the tube is said to be at saturation or plate saturation. Saturation is reached in a triode when the voltages on the grid and plate combine to draw all the electrons from the space charge. As the grid becomes less negative (between times c and d) and actually becomes positive (between times d and e), the plate current increases, the voltage across RL increases, and the plate voltage decreases.

Apparently, when the grid voltage reaches +12 volts at time e, the plate current reaches saturation. Maximum plate current (at saturation) results in maximum voltage across RL and minimum plate voltage. Any grid voltage higher than +12 volts cannot cause further changes in the output. Therefore, between times e and f, the plate voltage remains at +100 volts and the waveform is distorted. This is also amplitude distortion.

This has been an explanation of one cycle of an input signal that overdrives the tube. By means of the same circuit, a 50-volt peak-to-peak input signal caused a vastly different output from that caused by the 6-volt peak-to-peak input signal. The 6-volt peak-to-peak signal did not overdrive the tube. When the input signal was forced into cutoff, the grid was driven to -24 volts and into saturation when the grid was driven to +12 volts (the grid voltage plus the signal voltage). During these periods, the tube could not respond to the input signal. In other words, the output was distorted. A method commonly used to overcome distortion partially is to vary the bias voltage on the grid. The point at which the tube goes into cutoff or saturation can then be controlled. For this reason tube biasing is of great importance in most tube circuits.

Types of Biaffing

There are two main classes of biasing--fixed and self. In a tube circuit that uses fixed biasing, the grid biasing voltage is supplied from a power source external to the circuit. You are already familiar with battery biasing, which is one form of fixed biasing. When fixed biasing is used in a circuit, it can be represented as either a battery, as shown in diagram A, figure 1-21, or as a conductor connected to $-E_{CC}$ as shown in diagram B, figure 1-21. Fixed biasing is rarely used in electronics today. The most common type of biasing is called self-biasing. In circuits using self-biasing, the biasing voltage is developed across a resistor in the cathode or grid circuit by tube current. There are two main methods of self-biasing: cathode biasing and grid-leak biasing.

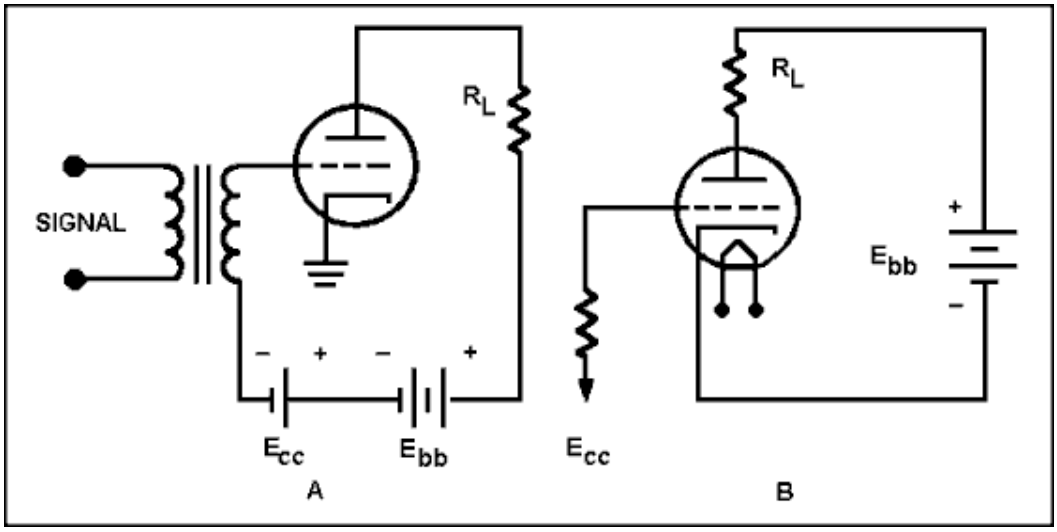


Figure 1-21. Fixed Bias.

Cathode Biasing. The first method to be discussed is cathode biasing. In circuits using cathode biasing, the cathode is made to go positive relative to the grid. The effect of this is the same as making the grid negative relative to the cathode. Because the biasing resistor is in the cathode leg of the circuit, the method is called cathode biasing or cathode bias. A triode circuit using cathode bias is shown in figure 1-22.

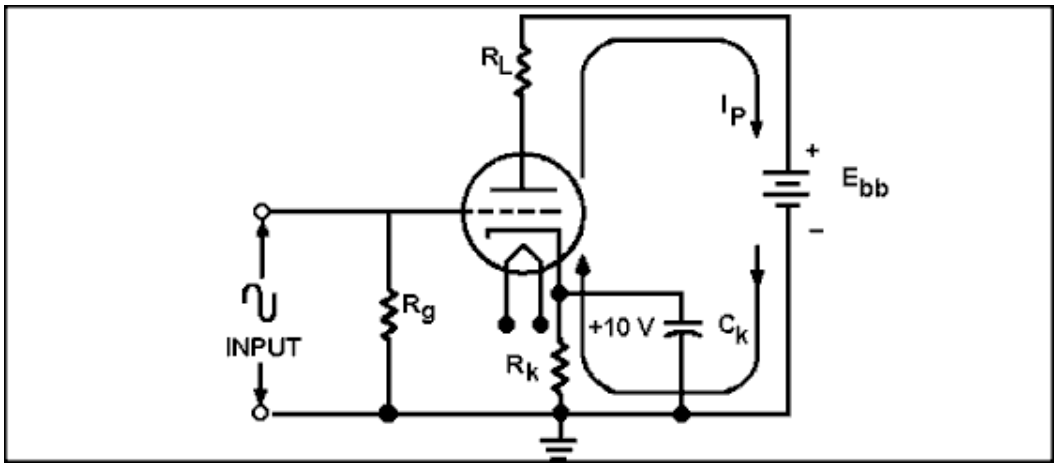


Figure 1-22. Cathode Bias.

The only difference between the illustrated circuit and the one used to demonstrate triode operation is the elimination of the battery E_{cc} and the addition of circuit components R_k, the cathode biasing resistor; C_k, the cathode ac bypass capacitor; and grid resistor R_g.

When the tube conducts, current flows from the battery through R_k to the cathode, through the tube to the plate, and through R_L to the positive terminal of the battery. The current flowing through R_k will cause a voltage drop across R_k. The bottom of R_k goes negative while the top goes positive. This positive voltage at the top of R_k makes the cathode positive relative to the grid.

C_k serves as an ac bypass. Without C_k, the bias voltage will vary with ac input signals. This is particularly troublesome in the higher frequencies like those found in radio receivers. R_k, the cathode biasing resistor, is used to develop the biasing voltage on the cathode.

The input signal is developed across R_g. Cathode biasing voltage is developed in the following manner. Bias voltage will vary with the input unless C_k, the cathode bypass capacitor, is used. To understand how the bias voltage will vary with an ac input signal, refer to figure 1-22. Note that under quiescent conditions, the voltage at the top of R_k is equal to 10 volts. When the positive-going signal illustrated to the left of the tube is applied, conduction through the tube will increase. The only problem is that current through R_k will also increase. This will increase the voltage drop across R_k, and the cathode voltage will now be greater than +10 volts. At this time the plate is going negative due to increased conduction through the tube. The combination of the negative-going plate and positive-going cathode will decrease the electrostatic attraction across the tube that will lower conduction of the tubes. The effect of this will be to reduce gain of the tube.

When the negative-going signal is applied, conduction through the tube decreases. Current through R_k decreases, and the voltage drop across R_k decreases. This causes the cathode to go more negative, which tends to increase conduction through the tube. The way a negative-going signal is amplified is by decreasing plate current and allowing the plate to go positive (remember the 180ø inversion). Thus, increasing conduction on the negative half-cycle decreases gain of the half-cycle. The overall effect of allowing cathode biasing to follow the input signal is to decrease gain of the circuit with ac input.

This problem can be overcome by installing C_k. The purpose of C_k is to maintain the cathode biasing voltage at a constant level. In common usage, the action of C_k is referred to as bypassing the ac signal to ground.

The action of Ck will be explained using figure 1-23. View A shows the circuit under quiescent conditions. With some conduction through the tube, the cathode and tops of R_k and C_k are at +10 volts.

In view B, the positive-going signal is applied to the grid. This causes increased conduction through the tube, which attempts to drive the cathode to +20 volts. The top of C_L is still at +10 volts (capacitors oppose a change in voltage). The top plate of C_k is in effect 10 volts negative in relation to the top of R_k. The only way that C_k can follow the signal on the top of R_k (+20 volts) is to charge through the tube back to the source and from the source to the lower plate of C_k. When C_k charges through the tube, it acts as the source of current for the cathode. This causes the cathode to remain at +10 volts while the capacitor is charging.

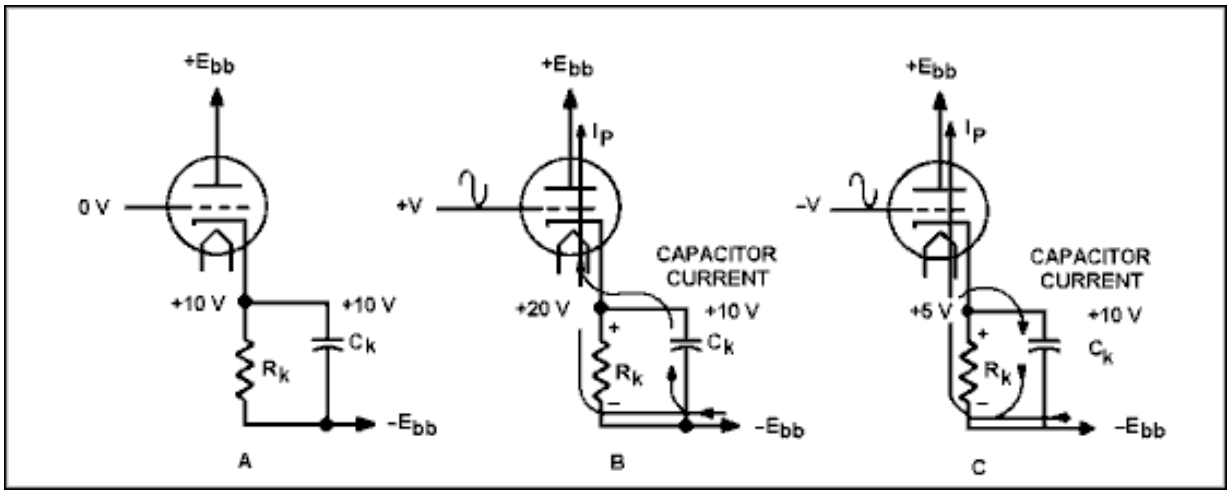


Figure 1-23. Effect of Bypass Capacitor.

View C of the figure shows the same circuit as before but with a negative going input signal. Under these conditions, conduction through R_k will decrease. This will cause a decrease in current flow through R_k. Decreased current means decreased voltage drop. The top of R_k will try to go to +5 volts. C_k must now go more negative to follow the top of R_k. To do this, current must flow from C_k through R_k to the top plate of C_k. This discharging of C_k will increase current flow through R_k and increase the voltage drop across R_k, forcing the top to go more positive. The voltage drop is due to current flow through the resistor. Thus, the cathode stays at +10 volts through the capacitor charge cycle.

There is one point that should be made; C_k and R_k are in parallel. Previous study shows that voltage in a parallel circuit is constant. Thus, it would seem impossible to have the top of R_k at one voltage while the top plate of C_k is at another. In electronics nothing happens instantaneously. There is always some time lag that may be measured in millionths or billionths of seconds. The action of C_k and R_k that was just described takes place within this time lag. To clarify the explanation, the voltages used at the components R_k and C_k were exaggerated. Long before a 10-volt differential could exist between the tops of R_k and C_k, C_k will have acted to eliminate this voltage differential.

The capacitor, then, can be said to regulate the current flow through the bias resistor. This action is considered as bypassing or eliminating the effect of the ac input signal in the cathode. For all practical purposes, assume that ac flows through the capacitor to ground. Note, however, that ac only appears to flow across a capacitor. In reality the ac signal is shunted around the capacitor.

There are two disadvantages associated with cathode biasing. To maintain biasing voltage continuously, current must flow through the tube, and plate voltage will never be able to reach the maximum value of the source voltage. This, in turn, limits the maximum positive output for a negative input signal (the 180° inversion). In addition, maximum plate voltage is decreased by the amount of cathode biasing voltage. If the cathode is biased at +20 volts, this voltage must be subtracted from the plate voltage. As an example, consider a triode with a 10,000-ohm plate resistor and a +300-volt dc source voltage. If a current of 2 milliamperes flows through the tube under quiescent conditions, 20 volts are dropped across the plate-load resistor. The maximum plate voltage is then 300 volts - 20 volts = 280 volts dc. Consider the 20 volts dropped across the cathode resistor. Plate voltage becomes 280 volts - 20 volts = 260 volts. To understand this more thoroughly, see figure 1-24. In view A, the source voltage is 300 volts dc. There are two ways of looking at this voltage: either the plate is at +300 volts and the cathode is at 0 volts (ground), or the plate is at +150 volts and the cathode is at -150 volts. In electronics, it is common practice to assume that the plate is at +300 volts while the cathode is at 0 volts. To simplify this discussion we will assume that the plate is at +150 volts, and the cathode is at -150 volts. The potential difference between plate and cathode is 300 volts. If a plate-load resistor is installed, as shown in view B, 20 volts are dropped by R_L. The potential difference between the plate and cathode is now 280 volts. In view C, R_k has now been placed in the same circuit. R_k drops volts. Therefore, the effect of cathode biasing is to reduce the maximum positive signal that the circuit can produce. In this case, the maximum positive signal has been reduced by 20 volts. Despite these disadvantages, cathode biasing has two main advantages: it is simple and it is economical.

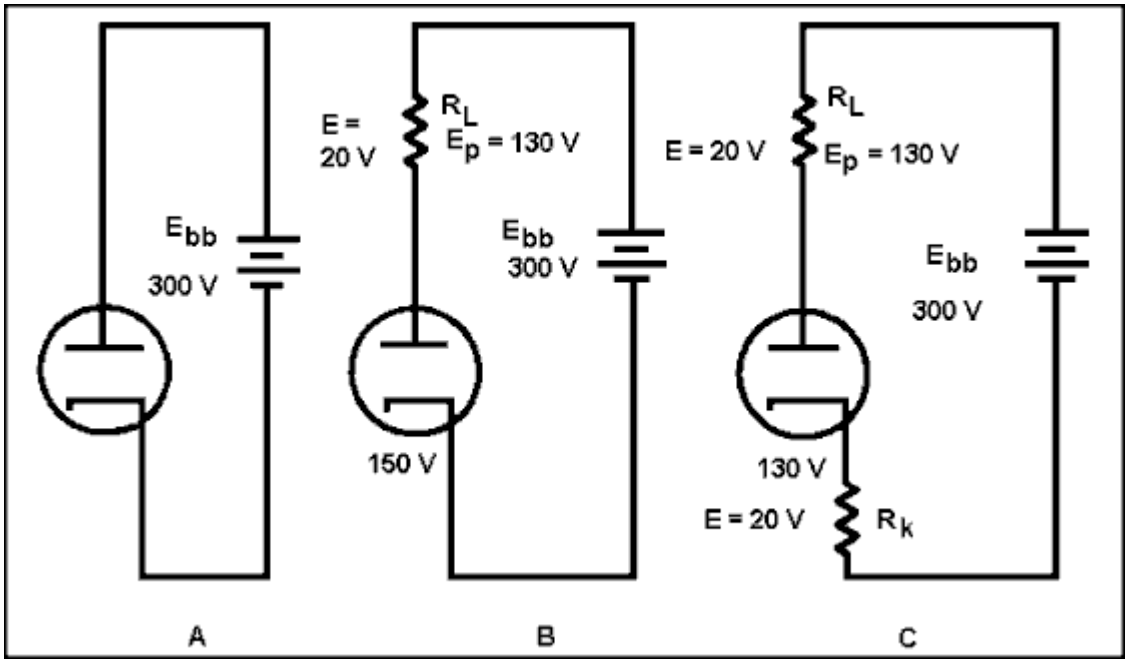


Figure 1-24. Loss Due to Cathode Biasing.

Grid-leak Biasing. The second type of self-biasing is grid-leak biasing. As the name implies, bias voltage is developed in the grid leg portion of the circuit. Bias voltage in this type of biasing is derived by allowing the positive input signal to draw grid current through a circuit made up of a resistor and a capacitor. There are two types of grid-leak biasing commonly in use: shunt and series..

Shunt Grid-leak Biasing. Figure 1-25 depicts a simplified triode circuit employing shunt grid-leak biasing. Because the bias is derived from the positive input signal through capacitive action, the input signal must go through several positive alternations before the final operating bias voltage is achieved.

View A of figure 1-25 shows the circuit under quiescent conditions. This circuit is similar to the one used when triode action was discussed. The only additions are the grid resistor R_g, coupling capacitor C_c, and resistance rgk. Resistance rgk doesn't exist as a physical component but is used to represent the internal tube resistance between the triode's cathode and grid. Electrically, rgk is very small, about 500 ohms. Under quiescent conditions, some conduction occurs through the tube.

Some electrons will strike the wires of the grid, and a small amount of grid current will flow through R_g to ground. This will cause the right-hand plate of C_c to go slightly negative. This slight negative charge will, in turn, keep the grid of the tube slightly negative. This limits the number of electrons that strike the grid wires.

In view B of figure 1-25, the first positive alternation of a series of ac alternations, EIN, is applied to the circuit. The positive-going voltage causes the left-hand plate of C_c to go positive. The left-hand plate must lose electrons

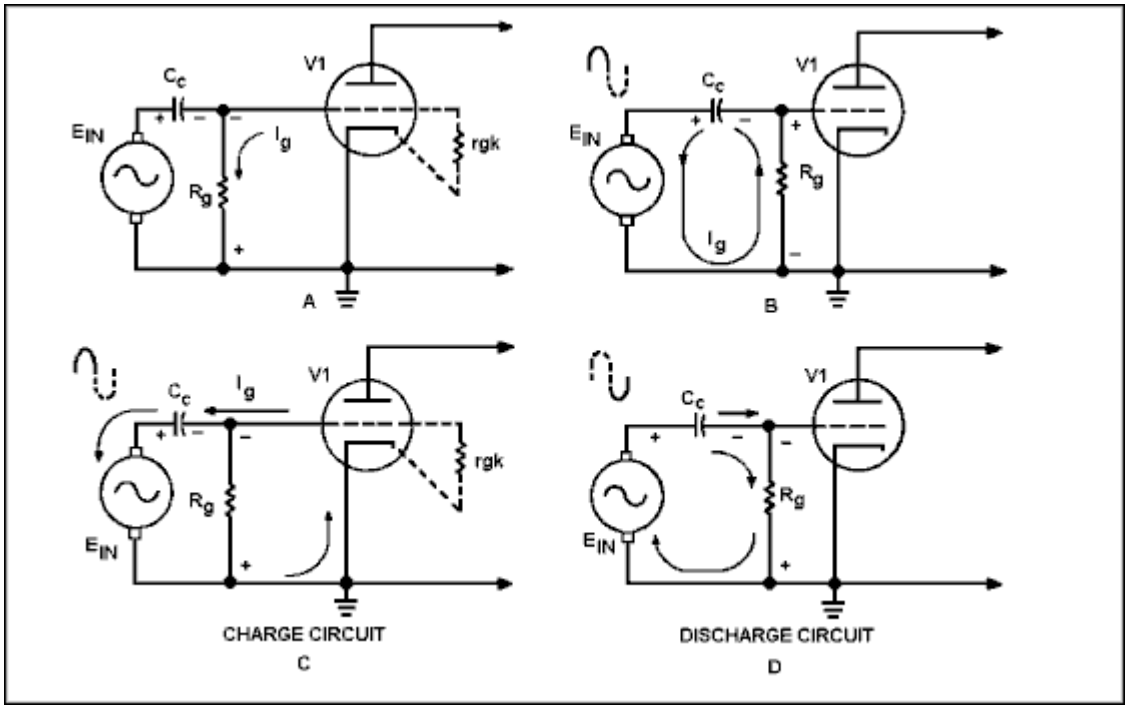


Figure 1-25. Shunt Grid-leak Biasing

to go positive. These electrons leave the left-hand plate of C_C and travel to an input source where they are coupled to ground. From ground, current flows through R_g causing a negative (bottom) to positive (top) voltage drop across R_g. In effect, the ac signal has been coupled across the capacitor. Because of this, capacitors are said to pass the ac signal while blocking dc. (In reality, the ac signal is coupled around the capacitor.) In view C of the figure, the positive-going voltage at the top of R_g will be coupled to the grid, causing the grid to go positive. The positively charged grid will attract electrons from the electron stream in the tube. Grid current will flow from the grid to the right-hand plate of C_C. This will cause the right-hand plate to go negative. (Electrostatic repulsion from the right-hand plate of C_C will force electrons from the left-hand plate of C_C, causing it to go positive.) The electrons will flow through the signal source, to ground, from ground to cathode, from cathode to grid, and finally to the right-hand plate of C_C. This is the biasing charge cycle. The charge current goes through the tube rather than through R_g for the following reason. When the grid goes positive in response to the positive-going input signal, electrostatic attraction between the grid and cathode increases. This, in turn, reduces the resistance (rgk) between the grid and cathode. Current always follows the path of least resistance. Thus, the capacitor charge path is through the tube and not R_g.

When the first negative alternation is applied to the circuit (view D), the left-hand plate of C_C must go negative. To do this, electrons are drawn from the right-hand plate. The electrons travel from the right-hand plate of C_C, through R_g, causing a voltage drop negative (top) to positive (bottom), and from the bottom of Rg through the source to the left-hand plate of C_g. C_g will discharge for the duration of the negative alternation. But, Cc can only discharge through R_g, which is a high-resistance path compared to the charge path. A study of capacitors shows that RC time constants and the rate of discharge increase with the size of R. C_C can therefore charge through the low resistance of rgk to its maximum negative value during the positive half-cycle. Because C_C discharges through R_g (the high-resistance path), it cannot completely discharge during the duration of the negative half-cycle. As a result, at the completion of the negative alternation, C_C still retains part of the negative charge it gained during the positive alternation. When the next positive alternation starts, the right-hand plate of C_C will be more negative than when the first positive alternation started.

During the next cycle, the same process will be repeated, with C_C charging on the positive alternation and discharging a lesser amount during the negative alternation. Therefore, at the end of the second cycle, Cc will have an even larger negative charge than it did after the first cycle. The charge on C_C will not continue to increase until the tube is forced into cutoff because of the following reason. As the negative charge on the right-hand plate of Cc forces the grid more negative, the cathode decreases. This, in effect, increases the resistance (rgk) between the cathode and grid until rgk becomes, in effect, the same size as R_g. At this point, charge and discharge Cc will equal one another and the grid will remain at some negative, steady voltage. What has happened in this circuit is that C_C and R_g, through the use of unequal charge and discharge paths, have acted to change the ac input to a negative dc voltage. The extent of the bias on the grid will depend on three

things: the amplitude of the input, the frequency of the input, and the size of R_g and C_C. This type of biasing has the advantage in that it is directly related to the amplitude of the input signal. If the amplitude increases, biasing increases with it. The main limiting factor is the amount of distortion that can be tolerated. Distortion occurs during the positive alternation when the grid draws current. Current drawn from the electron stream by the grid never reaches the plate; therefore, the negative-going output is not a faithful reproduction of the input while the positive-going output (during the negative input cycle) will be a faithful reproduction of the input. This is similar to the situation shown in the flattopped portion of the output signal in figure 1-20.

Series Grid-leak Biasing. The series grid-leak biasing circuit shown in figure 1-26 operates similarly to the shunt grid-leak circuit. When the first positive alternation is applied to the left-hand plate of the grid capacitor, Cg, the left-hand plate must lose electrons to go positive with the input. Electrons will leave the left-hand plate and flow through R_g, causing a negative (lefthand side) to positive (right-hand side) voltage drop. From the right-hand side of R_g the electrons will flow to the right-hand plate of C_g. The positive voltage developed at the right-hand side of R_g will be coupled to the grid. As the grid goes positive it will draw current, causing Cg to start to charge through the low-resistance path of the tube. During the negative alternation of the input, C_g will discharge through the high-resistance path of R_g. Once again it will not be completely discharged at the end of the negative alternation, and the capacitor will continue on its way toward charge quilibrium.

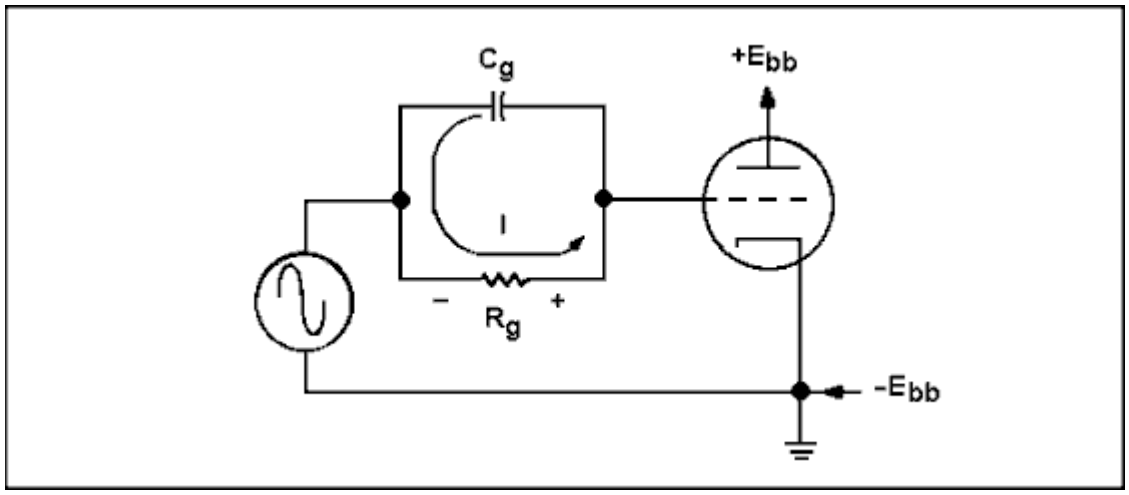


Figure 1-26. Series Grid-leak Biasing.

TUBE CONSTANTS

In the discussion of triodes, only the effects of the external circuit on the passage of current through the tube are considered. The behavior of the electron stream in a conducting tube is also under the influence of the physical structure of the tube. The effects that the physical structure of a tube have on the tube's operation are collectively called tube constants. Four of the most important of these tube constants are: transit time, amplification factor, transconductance, and interelectrode capacitance. An explanation of each of these four tube constants follows.

Transit Time

Unlike electron flow in a conductor, electrons in a vacuum tube do not move at the speed of light. Their velocity is determined by the potential difference between the plate and cathode. The amount of time it takes for the electrons to travel from the cathode to the plate is called transit time. As a result of this time difference, the appearance of a signal at the grid of a tube is not followed instantaneously by a change in current flow in the tube. Under normal conditions, the effect of this small time lag between the input signal and a change in tube current is unnoticed. At frequencies such as those used in radar equipment, this is not the case. Transit time at these frequencies has a very marked effect on tube operation. It is a major factor that limits the application of a given tube at higher frequencies.

Amplification Factor (Mu)

In the study of triodes so far, it has been seen that the output of a triode circuit is developed across the tube. The output is caused by the voltage dropped across R_L due to current flow from tube conduction. In all the demonstrations of gain, it was assumed that R_L was held constant, and current through the tube was varied. In this manner a voltage gain was achieved. If the resistance of R_L is changed by the designer, the gain of a triode circuit can be either increased or decreased. Assume that a circuit can be either increased or decreased and assume that a circuit is composed of a triode with a plate-load resistor of 100 K Ω. If a +2-volt signal causes 2 milliamperes to conduct through the tube, the voltage drop across R_L (the output) will be:

$$E = I \times R$$
$$E = I_p \times R_L$$
$$E = (2 \times 10^{-3} \text{ amperes}) \times (100 \times 10^{3} \text{ ohms})$$
$$E = 2 \times 100$$
$$E = 200 \text{ volts}$$
$$\text{Gain} = \frac{\text{output}}{\text{input}}$$
$$\text{Gain} = \frac{200 \text{ volts}}{2 \text{ volts}}$$
$$\text{Gain} = 100$$

Thus, the gain of the circuit is 100. If the plate-load resistor is reduced to 50 k Ω and the input is kept at +2 volts, the gain will be reduced to:

$$E = I_p \times R_L$$
$$E = (2 \times 10^{-3} \text{ amperes}) \times (50 \times 10^{3} \text{ ohms})$$
$$E = 2 \times 50$$
$$E = 100 \text{ volts}$$
$$\text{Gain} = \frac{100 \text{ volts}}{2 \text{ volts}}$$
$$\text{Gain} = 50$$

As you can see, voltage gain is dependent on both the tube characteristics and external circuit design. Voltage gain is a measure of circuit efficiency, not tube efficiency.

The actual characteristics of a tube are measured by two factors: mu(μ) or amplification factor and transconductance or g_m. The amplification factor (represented as μ) of a tube is measured by the ratio between a change in plate voltage and a change in grid voltage required to cause the same change of plate current. This is expressed mathematically as:

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

Figure 1-27, view A, shows a triode with a +1 voltage input signal. At this grid voltage, current through the tube is at 1 milliampere. The change in E_g (ΔE_g) is then 2 volts. This is shown in view B. Suppose that the grid voltage is returned to +1 volt, and plate voltage is increased until the ammeter in view C reads 2 milliamperes of plate current. At this point plate voltage has to be increased by 100 volts (350 - 250) to get the same change of plate current (1 mA). The change in plate voltages (ΔE_b) is then 100 volts. The amplification factor for just the tube is then equal to

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

$$\mu = \frac{100 \text{ volts}}{2 \text{ volts}}$$

$$\mu = 50$$

Note that mu is a measure of the ability of a tube to amplify. By comparing the mu of two different types of tubes, you can get an idea of their efficiency.

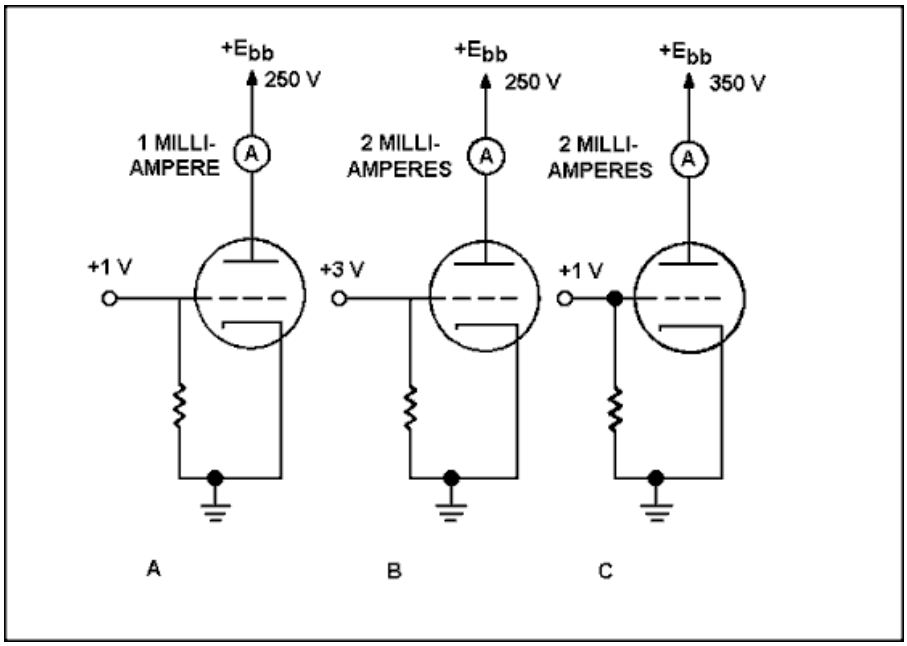


Figure 1-27. Obtaining Gain and Transconductance.

For example, assume you have two different tubes: one with a mu of 50 and the other with a mu of 100. If both tubes are placed in a circuit whose input varies by 2 volts, you can expect the following changes in plate voltage.

Tube 1:

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

$$\Delta E_p = \mu \text{ x } \Delta E_g$$

$$\Delta E_p = 50 \text{ x } 2 \text{ volts}$$

$$\Delta Ep = 100 \text{ volts}$$

Tube 2:

$$\mu = \frac{\Delta E_p}{\Delta E_g}$$

$$\Delta Ep = \mu \text{ x } \Delta E_g$$

$$\Delta Ep = 100 \text{ x } 2 \text{ volts}$$

$$\Delta Ep = 200 \text{ volts}$$

Thus, you can expect twice the change in plate voltage from tube 2 as from tube 1 for the same input voltage. Therefore, tube 2 will have twice the gain of tube 1.

Transconductance

Transconductance is a measure of the change in plate current to a change in grid voltage with plate voltage held constant. The unit for conductance is the mho (siemens) pronounced moe. Transconductance is normally expressed in either micromhos or millimhos. Mathematically, transconductance is expressed by the following formula:

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

Examine figure 1-27, views A and B, again. In view A, the input voltage is +1 volt. At +1 volt Eg, the plate current is equal to 1 milliampere with a plate voltage of 250 volts. In view B, the input voltage (E_g) is raised to +3 volts. E_g, as before, is equal to 2 volts. This increase in grid voltage causes plate current to increase to 2 milliamperes. The change in plate current (ΔI_p) is then equal to 1 milliampere. Thus, transconductance (g_m) is equal to:

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

$$g_m = \frac{1 \text{ milliampere}}{2 \text{ volts}}$$

$$g_m = .5 \text{ millimho}$$

$$\text{or } 500 \ \mu \text{ mhos}$$

The voltage gain of a circuit is measured by the ratio of the change in plate voltage versus the change in grid voltage. Because plate voltage is developed across a resistor, the more current varies with a given input signal, the greater will be the output (E = I x R). If there are two tubes, one with a gm

of 500 μ mhos and the other of 5000 μ mhos, the relative gain of these two tubes can be estimated. Assume that a circuit in one of these tubes will be used has a load resistor of 100 k Ω and that E_g will be 2 volts. The voltage gain of these two circuits will be:

Tube 1:

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

$\Delta I_p = E_g \times g_m$

$\Delta I_p = 2 \times .5$ millimho

$\Delta I_p = 1$ milliampere

$\Delta E_p = I_p \times R_L$

$\Delta E_p = (1 \times 10^{-3}$ amperes) x $(100 \times 10^3$ ohms)

$\Delta E_p = 100$ volts

$$\text{Gain} = \frac{\text{output}}{\text{input}}$$

$$\text{Gain} = \frac{100 \text{ volts}}{2 \text{ volts}} = 50$$

Tube 2:

$$g_m = \frac{\Delta I_p}{\Delta E_g}$$

$\Delta I_p = E_g \times g_m$

$\Delta I_p = 2$ volts x 5 millimhos

$\Delta I_p = 10$ milliamperes

$\Delta E_p = I_p \times R_L$

$\Delta E_p = (10 \times 10^{-3}$ amperes) X $(100 \text{ X } 10^3$ ohms)

$\Delta E_p = 1000$ volts

$$\text{Gain} = \frac{1000 \text{ volts}}{2 \text{ volts}} = 500$$

Note that tube 2 is 10 times the amplifier that tube 1 is.

Interelectrode Capacitance

Capacitance exists when two pieces of metal are separated by a dielectric. A vacuum has a dielectric constant of 1. Since the elements of the triode are made of metal and are separated by a dielectric, capacitance exists between them. This capacitance is called interelectrode capacitance and is schematically represented in figure 1-28.

There are three interelectrode capacitances involved in a triode. The capacitance between the plate and grid, designated C_{pg}, is the largest because of the relatively large area of the plate and, therefore, has the greatest effect on triode operation. The grid-to-cathode capacitance is designated C_{gk}. The total capacitance across the tube is designated C_{pk}.

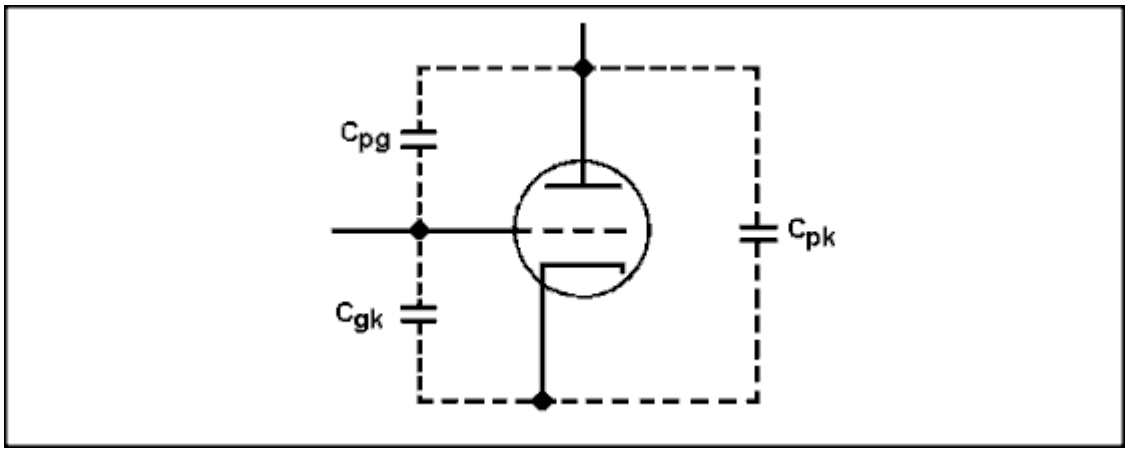


Figure 1-28. Schematic Representation of Interelectrode Capacitance.

C_{pg} has greater effect on the tube operation. This is because this capacitance will couple part of the ac signal from the plate back to the grid of the tube. The process of coupling the output of a circuit back to the input is called feedback. This feedback affects the gain of the stage. It may be desirable in some applications. In others, the effects must be neutralized. The effects of C_{pk} are greater at higher frequencies where X_C is lower.

MULTIPLE ELEMENT TUBES.

Tetrode Tube

Tetrodes were developed to compensate for the effects of interelectrode capacitance. Interelectrode capacitance cannot be eliminated from vacuum tubes, but it can be reduced. The easiest method found to reduce interelectrode capacitance is to split the capacitance between the grid and plate (C_{pg}) into two capacitors connected in series. This is done by placing an extra grid, called the screen grid, between the control grid and plate. This is shown in figure 1-29.

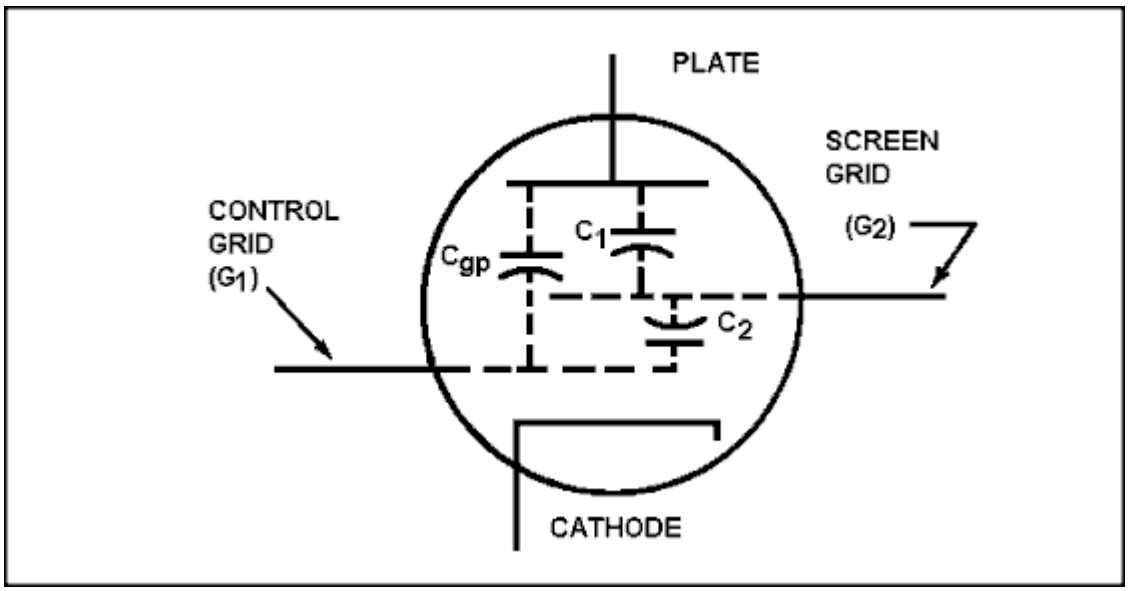


Figure 1-29. Effect of the Screen Grid on Interelectrode Capacitance.

The study of capacitance shows that connecting capacitors in series reduces the total capacitance to a value smaller than either of the capacitors. This is mathematically summed up as follows:

$$C_T = \frac{C1 \text{ X } C2}{C1 + C2}$$

The addition of the screen grid has the effect of splitting C_{pg} into two capacitances (C1 and C2) connected in series. Therefore, the total interelectrode capacitance between the control grid and plate is greatly reduced.

Operation of the Basic Tetrode Circuit. Figure 1-30 depicts a basic tetrode circuit. Only three components have been added to the triode: the screen grid, the screen grid dropping resistor, and the screen grid bypass capacitor (C_{sg}).

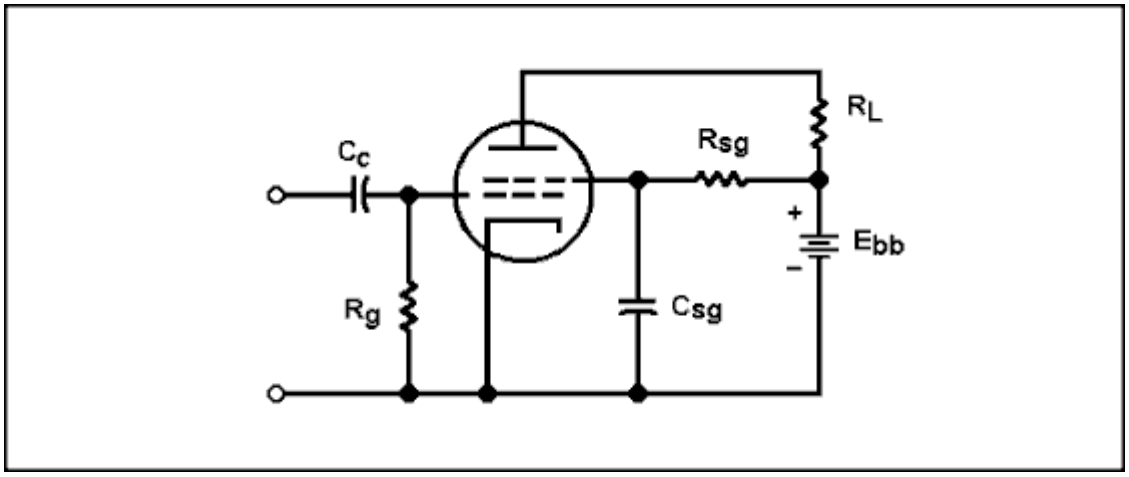


Figure 1-30. Basic Tetrode Circuit.

The problem now is, at what voltage and polarity should the screen grid be operated? If the screen grid were operated at a potential that would make it negative in relation to the control grid, it would act as a negative screen between the plate and control grid. As a result, gain would be reduced. If the screen grid were operated at plate potential, it would draw current from the electron stream when the tube conducts. Because of this, the value of R_{sg} is normally selected to cause the screen grid to be positive in relation to the control grid, but not as positive as the plate.

Despite this precaution, the screen grid still draws some current from the electron stream. Any signal applied to the control grid will appear at the screen grid inverted by 180ø from the input signal. This is undesirable, since it reduces the gain of the tube. Consider the effect if the control grid goes positive. Conduction through the tube increases, and since the screen grid is in the electron stream, it will draw some current. This causes the screen grid to go toward negative potential (less positive). The effect then is to place a negative-going electrode between the plate and positive-going control grid. The plate becomes partially screened by the negative-going screen grid, and again, gain will decrease. Because the signal at the screen grid is always 180° out of phase with the control grid, its effect will always be to oppose the effect of the control grid.

To overcome this, a bypass capacitor (C_{sg}) is connected between the screen grid and ground. The addition of this capacitor will shunt, or pass the ac variations on the screen grid to ground while maintaining a steady dc potential on the screen grid. In other words, C_{sg} removes all of the undesired effects mentioned in the previous paragraph.

One very useful characteristic of the tetrode tube is the relationship between the plate and screen grid. The screen grid will lessen the effect that a decreasing plate potential (negative-going signal) has on conduction through the tube. In a triode, when the grid goes positive, the plate goes negative. This decreases electrostatic attraction across the tube and tends to decrease the gain somewhat. In a tetrode, the screen grid has the ability to isolate the effect that ac variations on the plate have on the electron stream.

The positively charged screen grid will accelerate electrons across the tube even though the plate is negative going. As long as the plate remains positive in relation to the cathode, it will draw off these accelerated electrons. As a result, conduction through the tube when the plate is going negative will not be decreased. This is another big advantage of screen grid tubes.

Tetrode Characteristice. Because the screen grid is in the electron stream, it will always draw some current. The current drawn by the screen grid will be lost to the plate. This means that the transconductance of a tetrode, which is based on the amount of plate current versus control grid voltage, will be lower in tetrodes than in triodes. The formula for transconductance of a triode

$$gm = \frac{\Delta I_p}{\Delta E_g}$$

must be adjusted for screen grid current and becomes

$$\mathbf{gm} = \frac{\Delta \mathbf{I_p} - \Delta \mathbf{I_{sg}}}{\Delta \mathbf{E_g}}$$

The transconductance for a tetrode can never be as high as for a triode of similar construction.

While lowered transconductance in a tetrode is an undesirable characteristic, it is not the reason that tetrodes have found little acceptance in electronics. The factor that severely limits the operation of tetrodes is secondary emission.

Because the screen grid is positively charged, electrons traveling from the cathode to the plate are accelerated. Electrons are accelerated to such an extent that they dislodge electrons from the plate when they strike it. This is similar to the manner in which a high-velocity rifle bullet, fired into a pile of sawdust, throws sawdust about. Some of these electrons are fired back into the tube where they tend to accumulate between the screen grid and plate. This effect is most pronounced when the signal at the control grid is going positive and conduction through the tube is increasing. The plate in this situation is going negative in answer to the control grid signal. This causes the electrons accumulating between the plate and screen grid to be attracted to the screen grid. The current that is drawn by the screen grid is lost to the plate and gain is decreased. Gain is also decreased in another way. The negative charge accumulated by secondary emission causes some of the electrons (from the cathode) to be repelled from the plate, which further reduces gain.

Another undesirable characteristic of tetrodes associated with secondary emission is that the outputs are noisy. What this means is that small sporadic signals appear on the main output signal, as shown in figure 1-31.
When electrons are knocked from the plate, they represent losses of plate current and corresponding positive pulses on the output. Electrons falling back to the plate represent increases in plate current and cause negative going pulses to appear in the output. For these reasons tetrodes are used only in very specialized applications of electronics.

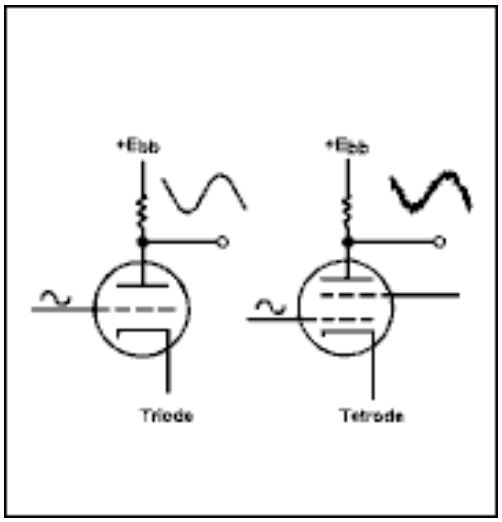


Figure 1-31. Noise in a Tetrode Circuit.

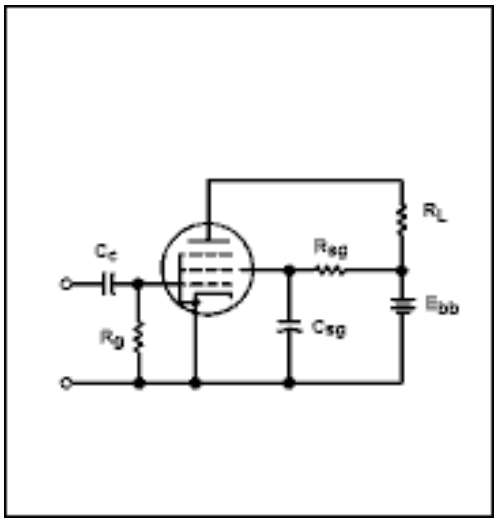


Figure 1-32. Basic Pentode Circuit.

Pentode Tube

The problem of secondary emission associated with the screen grid of a tetrode has been reduced by the addition of another grid. This third grid, called a suppressor grid, is placed between the screen grid and plate. The suppressor grid is normally connected either internally or externally to the cathode and bears the same charge as the cathode. This is shown in figure 1-32. Because of its negative potential (relative to individual electrons), any electrons that are emitted by the plate, through secondary emission, are repelled back toward the plate. Because the suppressor grid is negatively charged, it will not draw grid current. Additionally, the wide spacing between the meshes of the suppressor and its location between two positive elements of the tube ensure that the suppressor grid's effect on the electron stream will be minimum. Only the electrons emitted by secondary emission from the plate are affected by the suppressor grid. Because pentodes do not suffer from secondary emission, they have replaced the tetrode in most applications.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. Heating a conductor to a temperature sufficiently high to cause the conductor to give off electrons is called what?

   a. Secondary emission.
   b. Photoelectric emission.
   c. Thermionic emission.
   d. Interelectrode capacitance.

2. What undesirable effect is created in a tetrode tube by the screen grid?

   a. Interelectrode capacitance.
   b. Secondary emission.
   c. Thermionic emission.
   d. Photoelectric emission.

3. What component is used in a triode amplifier to convert variations in current flow to voltage variations?

   a. Plate.
   b. Plate-load resistor.
   c. Grid.
   d. Cathode.

4. What type of tube is shown in the illustration below?

   a. Diode.
   b. Triode.
   c. Tetrode.
   d. Pentode.

IMAGE: Figure 1-33.

5. What prevents a decrease in gain in a cathode biased vacuum tube?

   a.. Battery.
   b. Power supply.
   c. Cathode resistor.
   d. Bypass capacitor.

6. What is another name for the Edison effect?

   a. Thermionic emission.
   b. Photoelectric emission.
   c. Interelectrode capacitance.
   d. Secondary emission.

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7. Why is the control grid of a triode made negative with respect to the cathode?

a. To make the grid conduct more.
b. To prevent the grid from drawing current.
c. To allow the cathode to draw electrons from the grid.
d. To allow the plate to draw electrons from the grid.

8. How is cathode bias identified?

a. Cathode resistor.
b. Plate-load resistor.
c. Grid resistor.
d. Bypass capacitor.

9. The plate voltage of a tube will vary 126 volts when a 3-volt ac signal is applied to the control grid. What is the gain of this tube?

a. 42.
b. 46.
c. 52.
d. 56.

10. What is the suppressor grid normally connected to?

a. Cathode.
b. Plate.
c. Screen grid.
d. Control grid.

11. How is cathode bias developed in a vacuum tube?

a. By a battery.
b. By the power supply.
c. By current flow through the cathode resistor.
d. By current flow through the bypass capacitor.

12. If the mu of a tube is 85 and the signal at the control grid is 4 volts ac, the plate voltage will vary by what amount?

a. 300 volts.
b. 340 volts.
c. 360 volts.
d. 380 volts.

13. Why does the grid of a triode have a greater effect on electron flow than the plate?

    a. Because the plate voltage is not high enough.
    b. Because the grid is more positive than the plate.
    c. Because the cathode does not emit enough electrons.
    d. Because the grid is located closer to the cathode.

14. Why is a capacitor connected between the screen grid and ground in a tetrode tube screen circuit?

    a. To increase screen voltage.
    b. To decrease screen voltage.
    c. To maintain ac variations on the screen grid.
    d. To shunt ac variations on the screen grid to ground.

15. Transconductance is a measure of the relationship between what two factors?

    a. Changes in grid voltage and plate voltage.
    b. Changes in grid voltage and plate current.
    c. Changes in grid voltage and grid current.
    d. Changes in grid voltage and cathode current.

16. What type of bias requires constant current flow through the cathode circuit of a vacuum tube?

    a. Grid-leak bias.
    b. Fixed bias.
    c. Cathode bias.
    d. Self-bias and fixed bias.

17. What is the voltage drop across the plate-load resistor if the plate current is 20 mA and the plate-load resistor has a value of 10k ohms?

    a. 100 volts.
    b. 150 volts.
    c. 200 volts.
    d. 250 volts.

18. What is the result of adding a resistor in series with the plate circuit of a triode?

    a. It causes the plate current to decrease.
    b. It causes the plate current to increase.
    c. It causes a change in the voltage drop in the plate circuit.
    d. It causes the grid voltage to increase.

19. Why does the capacitor charge through the tube in grid-leak biasing?

    a. The grid resistor has a smaller resistance than the tube.
    b. The grid resistor has a higher resistance than the tube.
    c. The grid and tube resistance are equal.
    d. The grid does not draw circuit.

20. What is the disadvantage of an indirectly heated cathode?

    a. It takes longer to heat up to electron-emitting temperature.
    b. Alternating current cannot be used to heat the filament.
    c. The filament is closer to the plate than other parts.
    d. Direct current cannot be used to heat the filament.

21. At what point are all (or almost all) available electrons being drawn to the plate of a tube?

    a. Cathode saturation.
    b. Plate saturation.
    c. Filament saturation.
    d. Grid saturation.

22. What undesirable characteristic of a tetrode tube is reduced by the suppressor grid in a pentode circuit?

    a. Interelectrode capacitance.
    b. Secondary emission.
    c. Thermionic emission.
    d. Photoelectric emission.

23. What effect does adding a screen grid have on the interelectrode capacitance between control grid and plate?

    a. It increases.
    b. It decreases.
    c. It does not change.
    d. It depends on the size of the plate.

24. When does the capacitor charge in grid-leak biasing?

    a. During the positive and negative portions of the input signal.
    b. During the positive portion of the input signal.
    c. During the negative portion of the input signal.
    d. During the positive portion of the output signal.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect

Lesson 2

SPECIAL PURPOSE TUBES

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to determine the number and type of individual tubes contained within a single envelope of a multiunit tube; explain the function and operating principle of the beam power tube and the pentode tube; state the difference between the capabilities of conventional tubes and variable mu tubes; describe the construction of ultrahigh-frequency tubes and explain the effects that ultrahigh frequencies have on conventional tube operation; explain the operation of gas-filled diodes, thyratrons, and cold-cathode tubes; and explain the operating principles behind cathode ray tubes and the manner in which these tubes present visual display of electronic signals.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 3, 4, 5, 6, and 7 .

MULTIUNIT AND MULTIELECTRODE TUBES

One of the problems associated with electron tubes is that they are bulky. The size of an electron tube circuit can be decreased by enclosing more than one tube within a single envelope. There is a large variety of tubes that can be combined into this grouping of specialty tubes called multiunit tubes. Figure 2-1 shows the schematic symbols of a few of the possible combinations found in multiunit tubes.

An important point to remember when dealing with multiunit tubes is that each unit is capable of operating as a separate tube. But how it operates, either as a single tube or as a multiunit tube, is determined by the external circuit wiring. When you are analyzing the schematic of a circuit, simply treat each portion of a multiunit tube as a single tube, as shown in figure 2-2.

Another type of special purpose tube is the multielectrode tube. In some applications, tubes require more than the three grids found in conventional tubes. In some cases, up to seven grids may be used. These types of tubes are called multielectrode tubes and are normally classified according to the number of grids they contain. An example of this is illustrated in figure 2-3. The tube shown has five grids; hence, its name is pentagrid. The application of these tube types is beyond the scope of this subcourse; but because multielectrode tubes are commonly used, you should be aware of their existence.

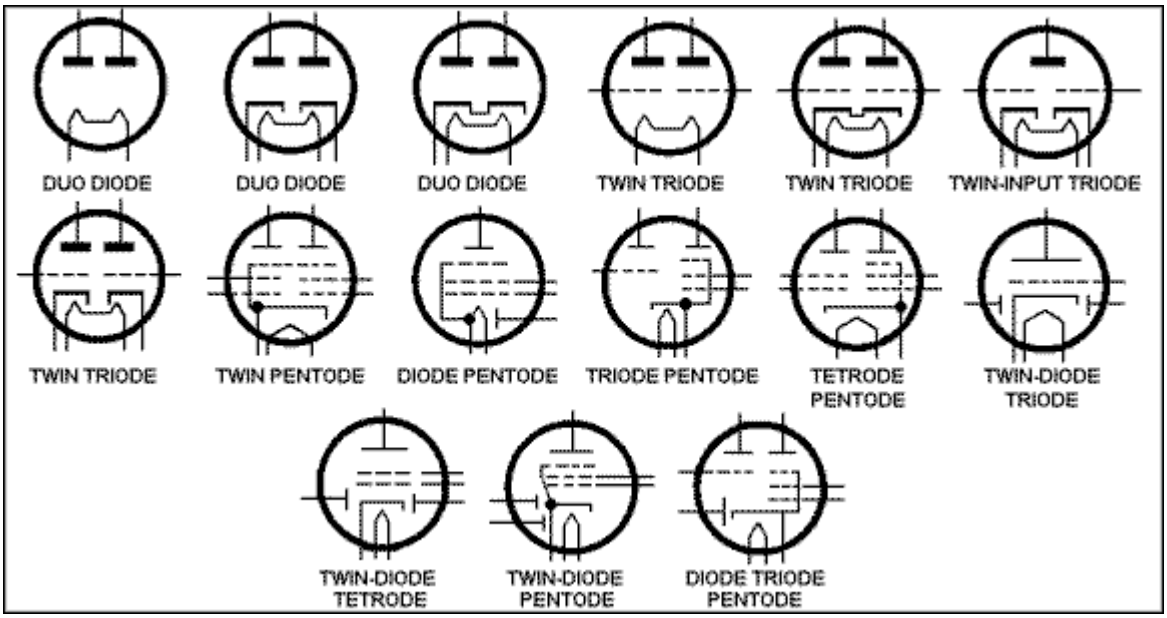

Figure 2-1. Typical Multiunit Tube Symbols.

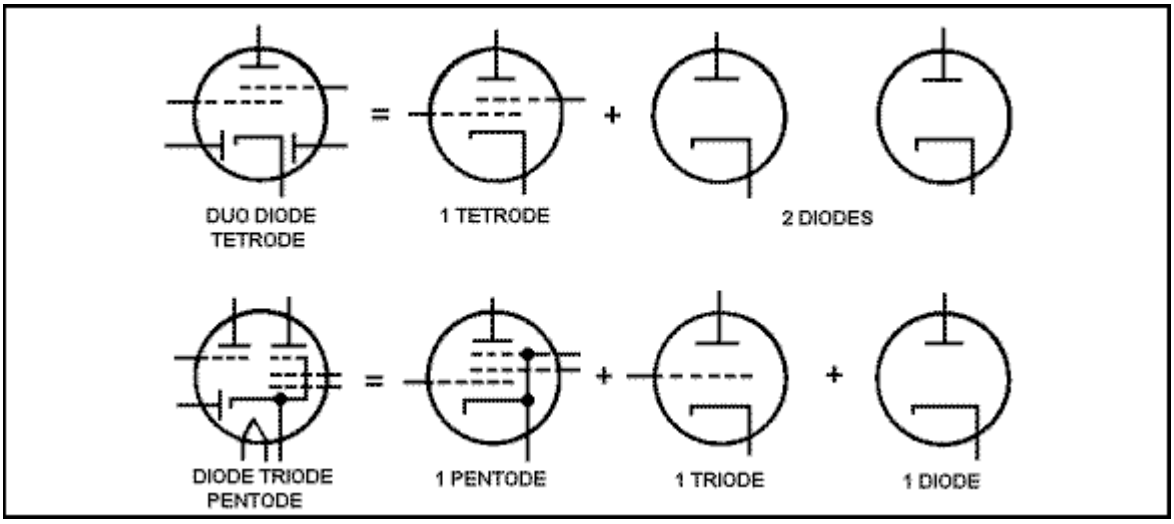

Figure 2-2. Multiunit Tube Identification.

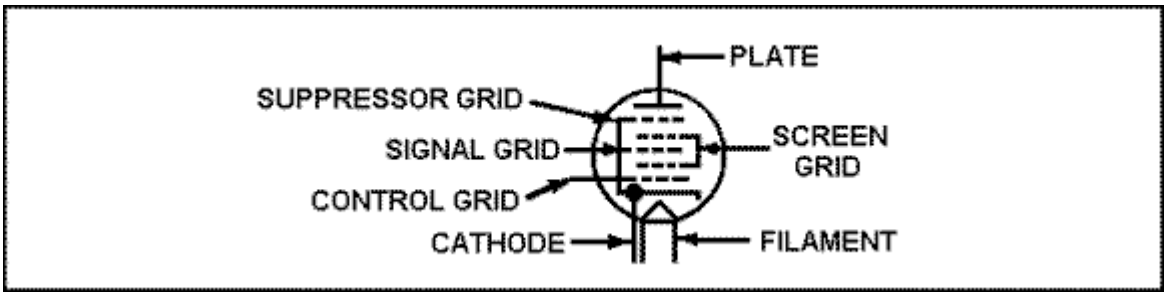

Figure 2-3. Pentagrid Multielectrode Tube.

BEAM POWER AND POWER PENTODE TUBES

The tube types you studied in the first lesson have one serious drawback; namely, they are not suitable as power amplifiers. Because of high-plate resistance and internal construction, tubes such as the triode, tetrode, and pentode are used only as voltage amplifiers. When power amplification is required (high-current requirements), special purpose tubes called beam power and power pentode tubes are used.

Figure 2-4 shows the arrangement of grids in a conventional pentode tube. The small circles depict cross sections of the grid. Each grid is offset, or staggered, from the grid directly behind it. This arrangement of grids permits each grid to be exposed to the electron stream flowing from cathode to plate. In this way, each grid will have maximum effect on the electron stream. There are two undesirable effects associated with this staggered grid arrangement that make it unsuitable for use in power amplifiers.

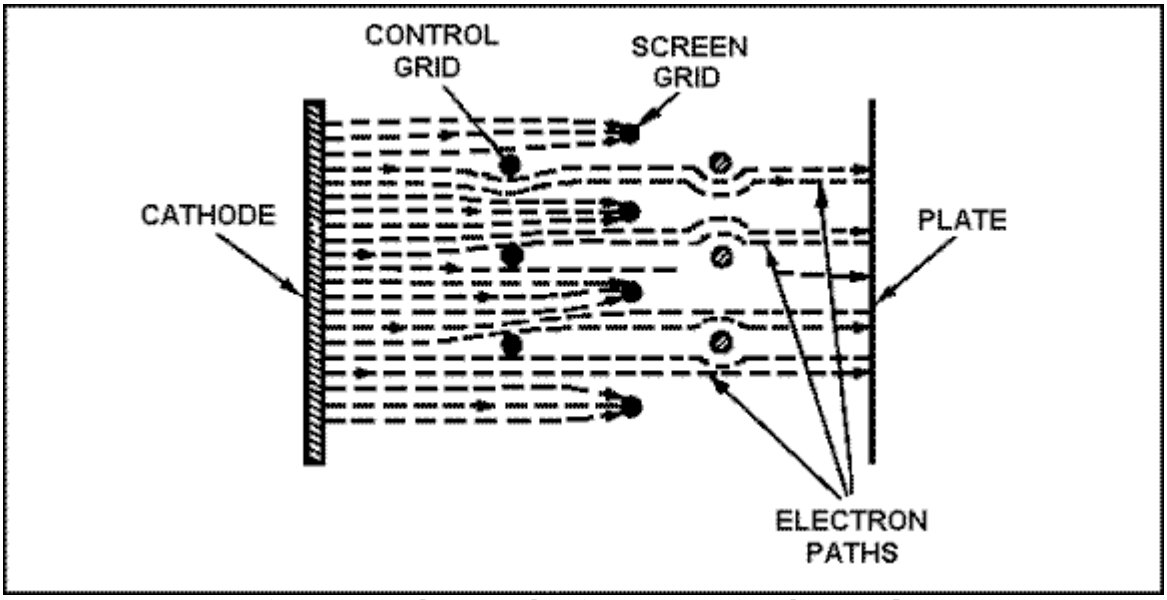

Figure 2-4. Electron Flow in a Conventional Pentrode.

First, no direct path exists between the cathode and plate. Electrons leaving the cathode must run an obstacle course around the grid wires to reach the plate. Some of these electrons are deflected by the grid and scattered and, thus, never reach the plate. Secondly, some electrons strike the grid wires and are removed from the electron stream as grid current. Because of these two undesirable effects, the amount of plate current that can flow through the tube is greatly reduced. Because of this loss of electrons from the stream, conventional tetrodes and pentodes are not suitable for power. Therefore, the beam power and power pentode tubes have been developed to overcome these problems.

Figure 2-5 shows the cross section of the power pentode. There is no staggered grid arrangement. Instead, each grid wire is directly in line with the grid in front and behind it. The screen and suppressor grids are shielded from the electron stream by the control grid. Because the screen grid is shielded by the control grid, it can draw little grid current from the electron stream.

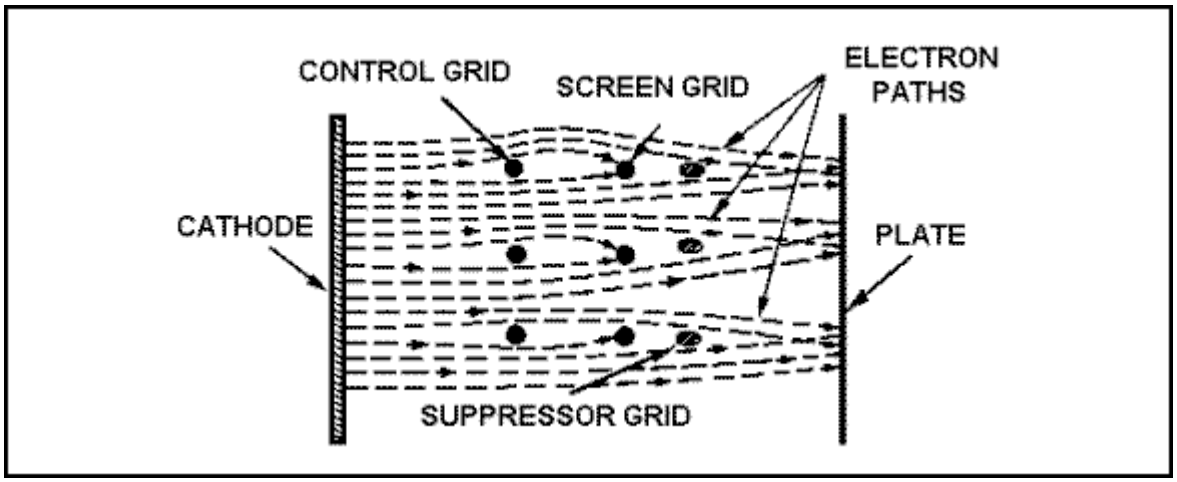

Figure 2-5. Electron Flow in a Power Pentode.

This arrangement of grids offers few obstacles to electron flow. Electrons will flow in sheets between the grid wires to the plate. The effect is to allow more of the electrons leaving the cathode to reach the plate. Thus, the tube has the advantage of high-power output and high efficiency. An added advantage to this type of grid arrangement is high-power sensitivity. This means that the tube can respond to smaller input signals than the conventional electron tube. The reason for this is obvious: many more electrons reach the plate from the cathode. Therefore, large plate currents can be obtained from relatively weak input signals.

Beam power tubes have the same grid arrangement as the power pentodes. In addition, they use a set of beam-forming plates to force the electron stream into concentrated beams. Figure 2-6 depicts the internal construction of a beam-forming tube and its schematic representation. The beam-forming plates surround the grids and their supporting structures and are internally connected to the cathode. This internal connection ensures that the beam forming plates are at the same negative potential as the cathode. Electrons that are emitted from the sides of the cathode are repelled away from the grid supports and into the electron stream by the negative charge on the beam-forming plates. Electrons pass to the plate through the spaces between the beam-forming plates and, by doing so, they are concentrated into beams. Because the beam-forming plates are at a negative potential, any electrons emitted by secondary emission are repelled back to the plate. The effect of the beam-forming plates is to increase the number of electrons in the electron stream by forcing stray electrons emitted from the sides of the cathode away from the grid supports and into the electron beam. Electrons that are deflected from the grid wires are also forced into the beam. This increases the total current flowing to the plate. For this reason, both beam-forming and power pentodes are suitable for use as power amplifiers.

VARIABLE MU TUBES

In most electron-tube circuits, the operating level of a tube is determined by the level of bias. When a negative-bias voltage is applied to the control grid of a tube, with no input signal, the conduction through the tube is reduced.

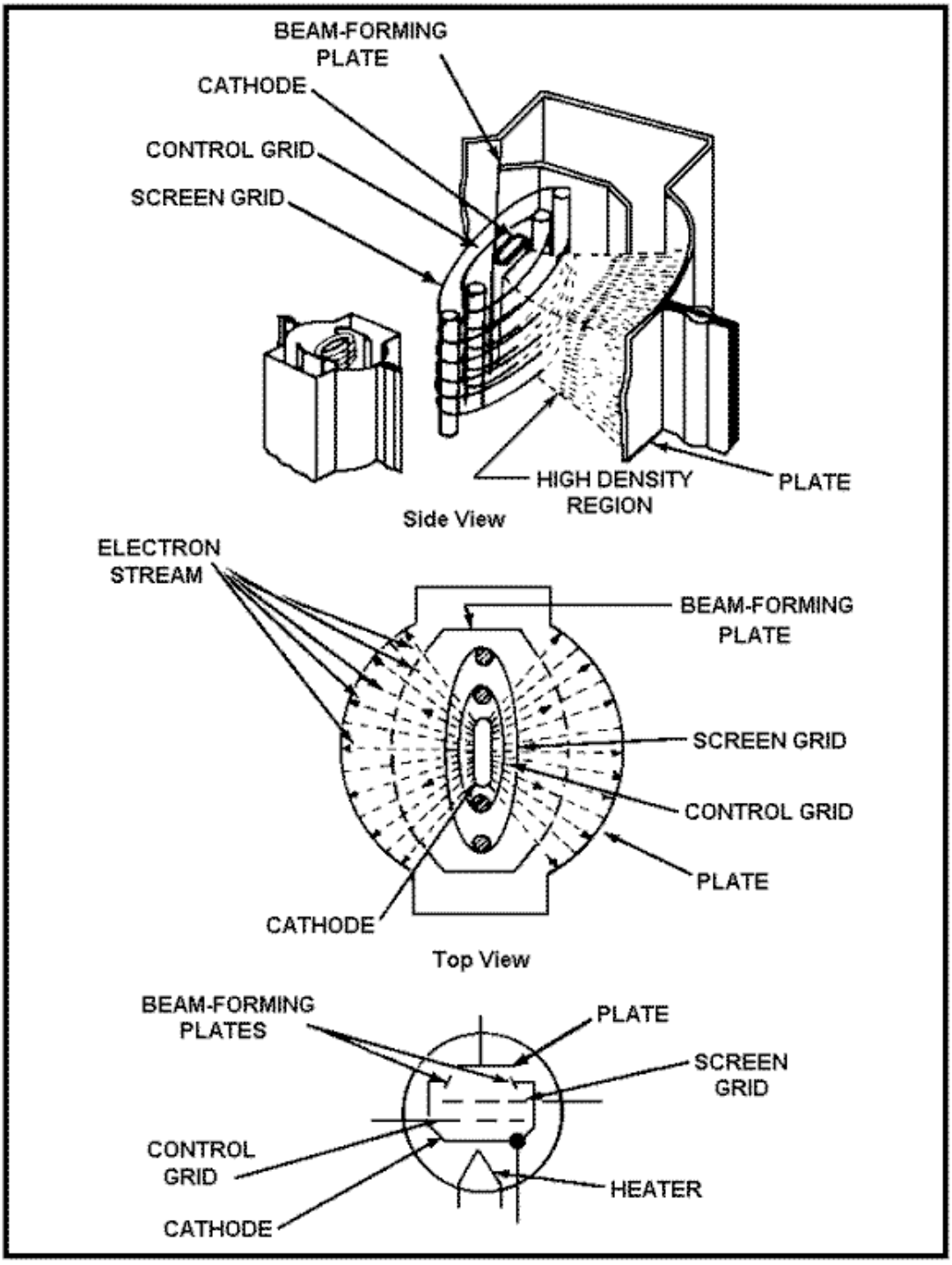

Figure 2-6. Beam Power Tube.

Thus, the damage to the tube is minimized. There is one drawback to this. Because the control grid is already negatively charged by the bias voltage, the negative alternation of a large input signal will drive the tube into cutoff long before the positive alternation can drive the tube into saturation. Once the negative alternation reaches a certain level (determined by the bias voltage and tube characteristics), the tube simply cuts off. For this reason conventional tubes are called sharp cutoff tubes. Because of sharp cutoff, the range of amplification of the conventional tube is limited by the bias voltage and tube characteristics. Once this range is exceeded, the output becomes distorted due to cutoff.

In most applications, the sharp cutoff feature of conventional electron tubes causes no problems. However, in some applications electron tubes are required to amplify relatively large input signals without distortion. For this reason, the variable mu tube was developed. Variable mu tubes have the ability to reduce their mu (æ) as the input signal gets larger. As the mu decreases, the likelihood that the tube will be driven into cutoff decreases. (For an amplifier, this may appear to be self-defeating, but it isn't.) The idea is to amplify large input signals as much as possible without causing the tube to cut off or create distortion. Because of their ability to avoid being driven into cutoff, variable mu tubes are called remote cutoff tubes. A variable mu tube can be driven into cutoff, but the amplitude of the input signal required to do so is considerably greater than in conventional sharp cutoff tubes.

The key to the ability of a variable mu tube to decrease gain with an increase in the amplitude of the input lies in its grid construction. To understand how the unique grid construction of a variable mu tube works, we will first examine the grid operation of a conventional tube during cutoff. Shown in figure 2-7 is a diagram of a conventional sharp cutoff triode with zero volts applied to the control grid. In view A, the majority of the electrostatic lines of force leave the positive plate (+) and travel unhindered between the evenly spaced grid wires to the negative cathode (-). Electrons emitted by the cathode travel along these lines from the cathode, through the grid spacings, to the plate.

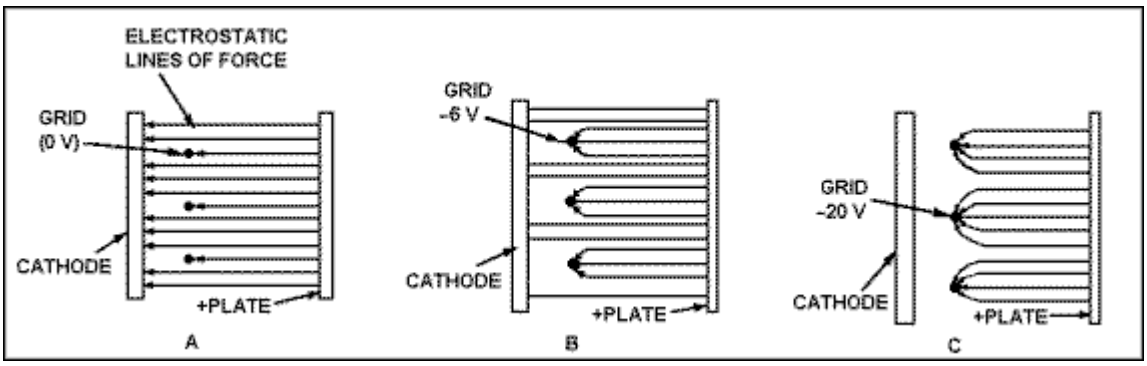

Figure 2-7. Cutoff in a Conventional Tube.

In view B, a bias voltage of -6 volts is applied to the grid. Some of the electrostatic lines of force are attracted to the negatively charged grid wires while the rest pass through the grid spacings. Because there are fewer lines of force reaching the cathode, there are fewer paths for electrons to use to reach the plate. As a result, conduction through the tube is decreased.

In view C, the negative potential of the grid has been raised to -20 volts, which drives the tube into cutoff. All of the electrostatic lines of force terminate at the negatively charged grid, instead of continuing on to the cathode. The electrons emitted by the cathode will not feel the electrostatic attractive force of the positively charged plate. Under these conditions, current cannot flow through the tube.

Shown in figure 2-8 is a diagram of a variable mu, or remote cutoff tube. The only difference between the remote cutoff tube depicted and the sharp cutoff tube is in the grid wire spacing. In the conventional sharp cutoff tube, the grid wires are evenly spaced while in the remote cutoff tube the grid wires in the middle of the grid are placed relatively far apart. This is shown in view A.

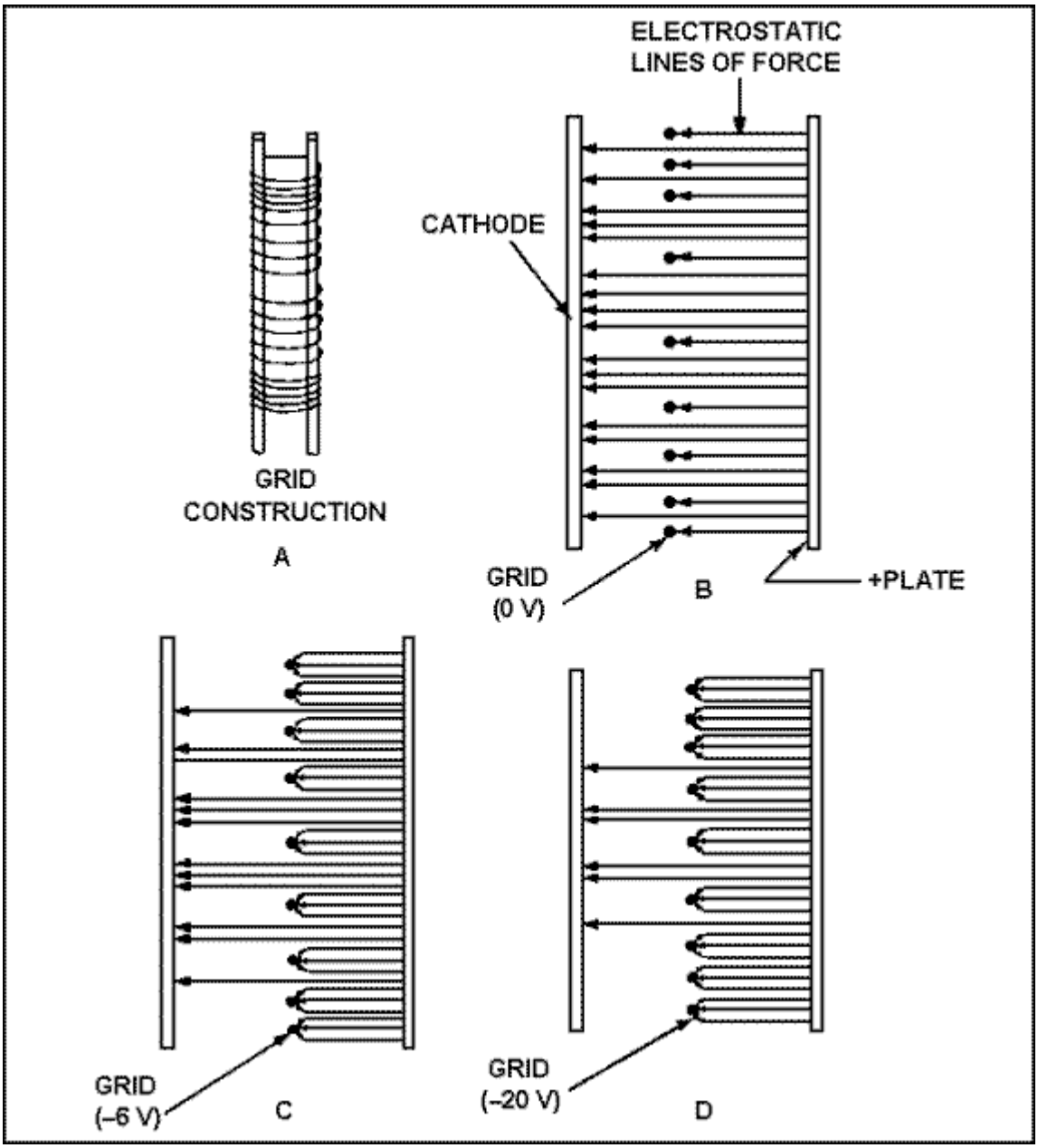

Figure 2-8. Grid Operation in a Remote Cutoff Tube.

In view B the control grid is at zero potential (0 volts). Just as in the sharp cutoff tube, electrons leave the cathode and travel along the lines of electrostatic attraction through the spaces between the grid wires to the plate. In view C a bias voltage of -6 volts is applied to the grid. Because of the close spacing of the grid wires at the ends of the grid, electrostatic lines of force at the ends are effectively terminated. The lines of force can only pass between the widely spaced grid wires closer to the center of the grid.

In view D the same negative potential (-20 volts) is applied to the grid that caused the conventional sharp cutoff tube discussed earlier to go into cutoff. This voltage is high enough to terminate most of the electrostatic lines of force on the grid wire. But, because of the wide spacing between the center

grid wires, some electrostatic lines of force are still able to pass between the center grid wires and reach the cathode. Conduction will still occur in the tube, but at a reduced level. If the grid is driven even more negative, lines of force will be blocked from reaching the cathode except at the very center of the grid. The remote cutoff tube, by its ability to reduce gain (conduction), handles large signals without going into cutoff. A variable mu tube with -3 volts applied to the grid will have a transconductance of about 2000 æmhos. If the grid is driven to -35 volts, the transconductance of the tube will decrease to 10 æmhos. This same increase in negative grid voltage would have driven a conventional tube into cutoff long before reaching -35 volts.

SPECIAL ULTRAHIGH-FREQUENCY (UHF) TUBES

Some of the limitations of conventional electron tubes were discussed earlier. One of these limitations was that the conventional tube was not able to operate (amplify) at extremely high frequencies such as those used in radar equipment. Even at frequencies lower than those used in radar equipment, problems occur. For example, at ultrahigh frequencies (300 MHz to 3000 MHz) transit time effects make the operation of a conventional electron tube impossible. For this reason, the special ultrahigh-frequency tubes were developed to operate within this frequency range.

In view A of figure 2-9, the positive-going alternation of a UHF ac signal is

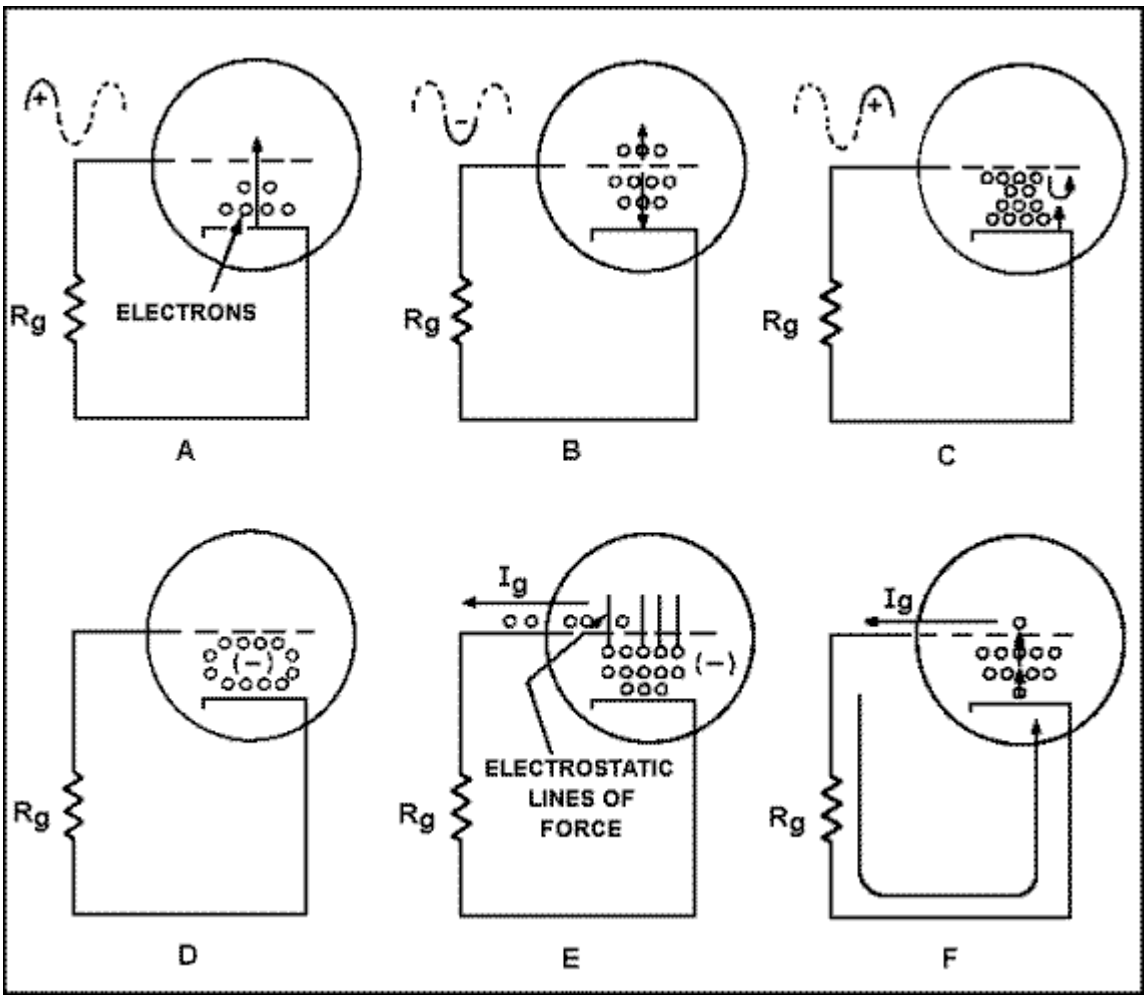

Figure 2-9. Effect of Transit Time at Ultrahigh Frequencies.

applied to the grid of a conventional triode tube. The first positive-going alternation reduces the negative bias on the grid, and electrons start to move toward the grid. Since the input is an ultrahigh-frequency signal, the majority of the electrons cannot pass the grid before the input signal progresses to the negative alternation. The electrons that have not yet passed the grid are either stopped or repelled back toward the cathode. This is shown in view B. Before these electrons can move very far, the second positive alternation reaches the grid and causes even more electrons to move from the cathode (view C). At the same time, the electrons that were repelled from the grid toward the cathode by the first negative alternation feel the effect of the positive-going grid. These electrons reverse direction and again move toward the grid. Because these electrons had to first reverse direction, they are now moving slower than the electrons that are attracted from the cathode by the second positive alternation. The result is that the electrons from the cathode catch up to the slower moving electrons, and the two groups combine (view C). This action is called bunching.

In effect, the area between the grid and cathode becomes highly negatively charged, as shown in view D. This negative charge is surrounded by an electrostatic field. The electrostatic field cuts the grid and repels electrons that are present in the grid. As electrons are forced from the grid, the grid tries to go positive. Unfortunately, this tendency toward a positive charge attracts electrons from the mass or bunched charge. Thus, as an electron is forced from the grid; it is replaced by another from the massed charge. Electrons forced from the grid represent grid current (Ig), as shown in view E. The grid current flows from the grid through Rg, to the cathode, from the cathode, to the massed charge, and back again to the grid. The movement of current in this manner is, in effect, a path for current flow from the cathode to the grid. Because current flows between the cathode and grid, the resistance (rgk) between these elements is lowered to the point of a short circuit. The grid, in effect, is short circuited to the cathode and ceases to function; and this, in turn, lowers tube efficiency dramatically. This is shown in view F of figure 2-9.

Transit time may be decreased by reducing the spacing between electrodes or by increasing the electrode voltages, which in turn increases electron velocity through the tube. The problem with this solution is that the tube does not present an infinite resistance to current flow. If the operating voltage is raised to an operating potential that is too high, arcing (arc-over) occurs between the cathode and plate and, most likely, will destroy the tube. For this reason, the effects of transit time are reduced in UHF tubes by placing the tube elements very close together.

Types of UHF Tubes

UHF tubes have very small electrodes placed close together and often are manufactured without socket bases. By reducing all the physical dimensions of the tube by the same scale, the interelectrode capacitance and transit time effects are reduced, without reducing the amplification capability of the tube. A disadvantage to this type of tube construction is that the power handling capability of these tubes is also reduced due to the close placement

of the tube elements. UHF tubes are placed in three broad categories based on their shape or construction, or both: acorn, doorknob, and planar.

Acorn Tubes. These tubes (figure 2-10) are available for use as diodes, triodes, or pentodes. Acorns are very small tubes that have closely spaced electrodes and no bases. The tubes are connected to their circuits by means of short wire pins that are sealed in the glass or ceramic envelope. Because of their small size, acorn tubes are usually used in low-power UHF circuits.

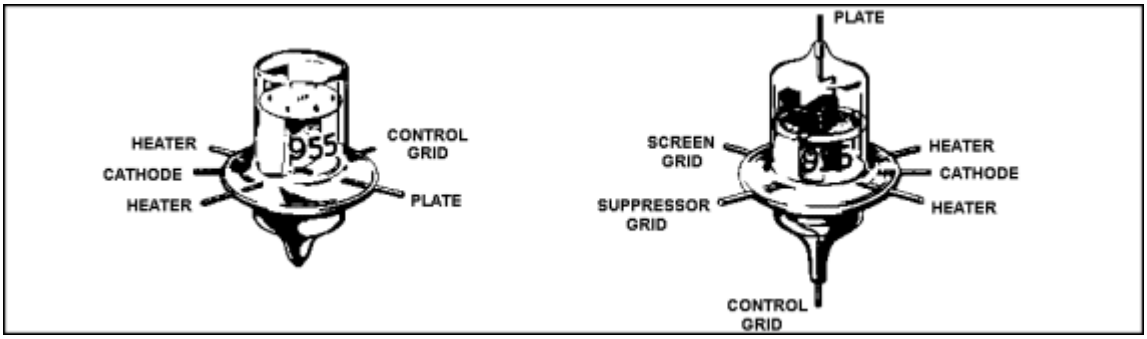

Figure 2-10. Acorn Tubes.

Doorknob Tubes. These tubes are enlarged versions of acorn tubes. Because of their larger physical size, they can be operated at higher power than acorn tubes.

Planar Tubes. Planar tubes are so named because of their construction. The ordinary (conventional) tube presented earlier uses concentric construction. This means that each element (cathode, grid, and plate) is cylindrical in shape. The grid is placed over the cathode; and the plate, which is the largest cylinder, is placed over the grid. The result is a tube composed of concentric cylinders like the one shown in figure 2-11.

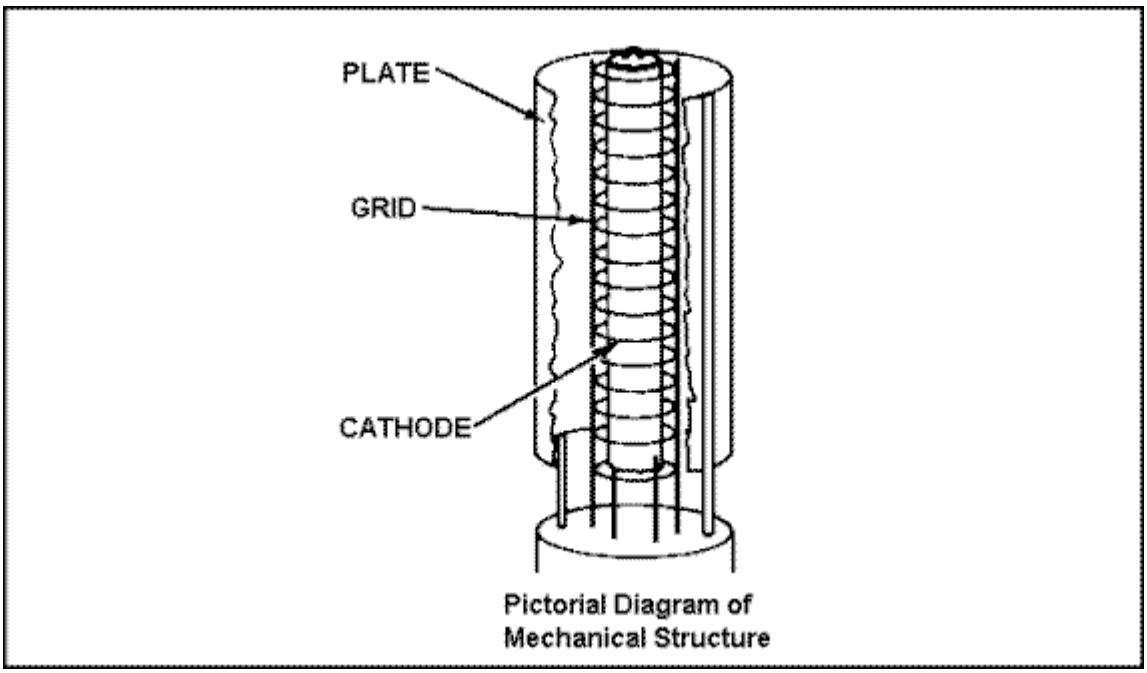

Figure 2-11. Concentric Construction of a Conventional Tube.

At ultrahigh frequencies, the problem of producing small tube elements while reducing the spacing between elements becomes very difficult. Not only are the elements hard to keep parallel with each other during the manufacturing process, they also have a tendency to warp and sag under normal operating conditions. Since these elements are already as close together as possible, any reduction in element spacing can cause arcing. Therefore, the planar tube was developed to prevent arcing or element sagging in conventional tubes.

Planar tubes are electron tubes in which the cathode, plate, and grid are mounted parallel to each other. Their physical construction greatly resembles a schematic diagram of a normal tube, as shown in figure 2-12. A typical planar tube is depicted in figure 2-13. Note that the tube elements are mounted close to each other and are parallel to one another. The oxide coating of the cathode is applied to the top surface only. Therefore, the emitting surface of the cathode is parallel to the plate and grid.

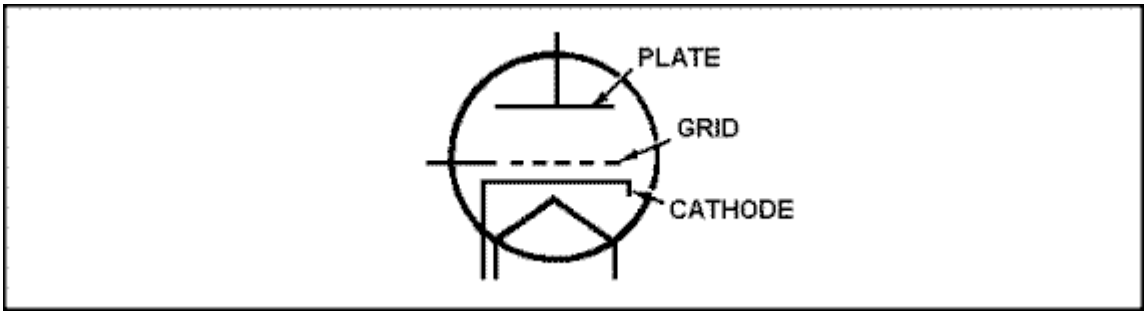

Figure 2-12. Resemblance of a Planar Tube to a Schematic Diagram of a Normal Tube.

The plate of the tube consists of a cylindrical stud. This stud plate construction has two purposes. Its flat lower surface serves as a parallel plate, and its external upper end serves as the external plate connection from the tube to the circuit. Because of its construction, the planar tube cannot use the familiar ladder type of grid. Instead, the grid, formed into a circle, is composed of a wire mesh similar to that of a common screen door.

The cathode structure is manufactured in two parts. Point A of figure 2-13 is the metallic shell of the tube and is used to couple (or connect) unwanted radio frequency signals from the cathode to ground. This connection is not, however, a direct coupling. The wafer at point C of figure 2-13 is composed of mica that serves as a dielectric. The lower extension of the cathode serves as one plate of the capacitor, while the other plate is formed from the flattened upper portion of the cathode connector ring. The cathode has a direct connection to the tube pin through the connector labeled point B. At high frequencies, the wiring of a circuit can pick up radio frequency signals and retransmit them. If the wiring involved happens to be the wiring used to supply dc voltages to the circuit, all the tubes in the circuit will receive the signal. The result will be massive distortion throughout the circuit.

The problem of massive distortion can be eliminated by isolating the dc and radio frequency circuits from each other. In planar tubes, this is fairly simple. The ring at point A is grounded. Any RF signals that the cathode may

pick up through tube conduction are grounded or shorted to ground through the capacitive coupling with the point A shell. In other words, the shell (capacitive ground) at point A serves the same function as the bypass capacitor in a cathode-biased circuit. Because the capacitor will not pass dc, bias voltages can be applied to the cathode through the tube pins.

Note the external shape of the planar tube in figure 2-13. The tube is composed of five sections, or cylinders. As you go from the top to the bottom, each cylinder increases in diameter. Because of this piled cylinder construction, the tube resembles a lighthouse, and is therefore known as a lighthouse tube.

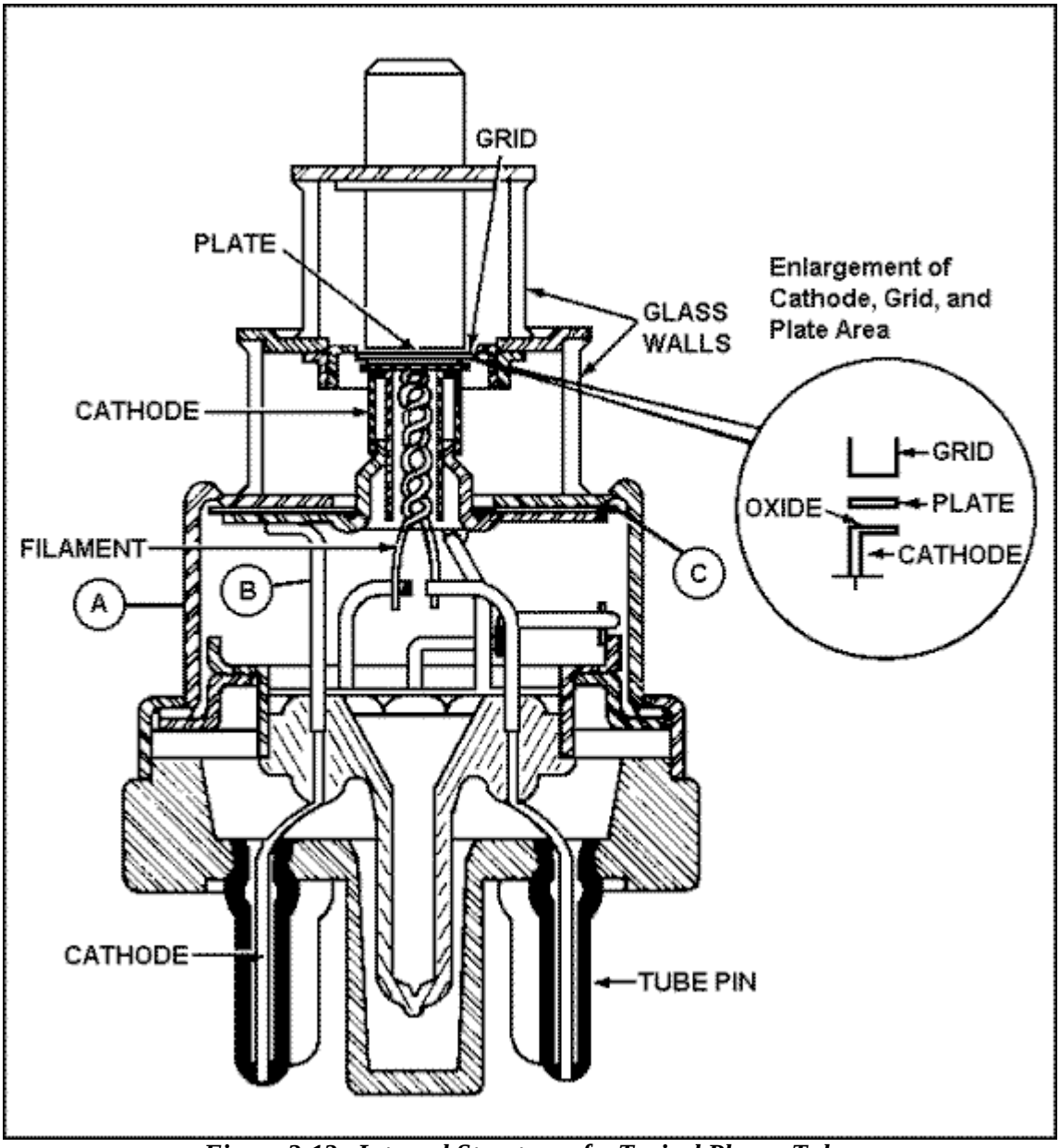

Figure 2-13. Internal Structure of a Typical Planar Tube.

Another type of planar tube is shown in figure 2-14. This type of tube, because of its external appearance, is called an oilcan tube. The major difference between it and the lighthouse tube is the addition of cooling fins mounted on the tube that enable it to handle more power than the light-house tube. Because of their planar construction, both types of tubes are capable of handling large amounts of power at ultrahigh frequencies.

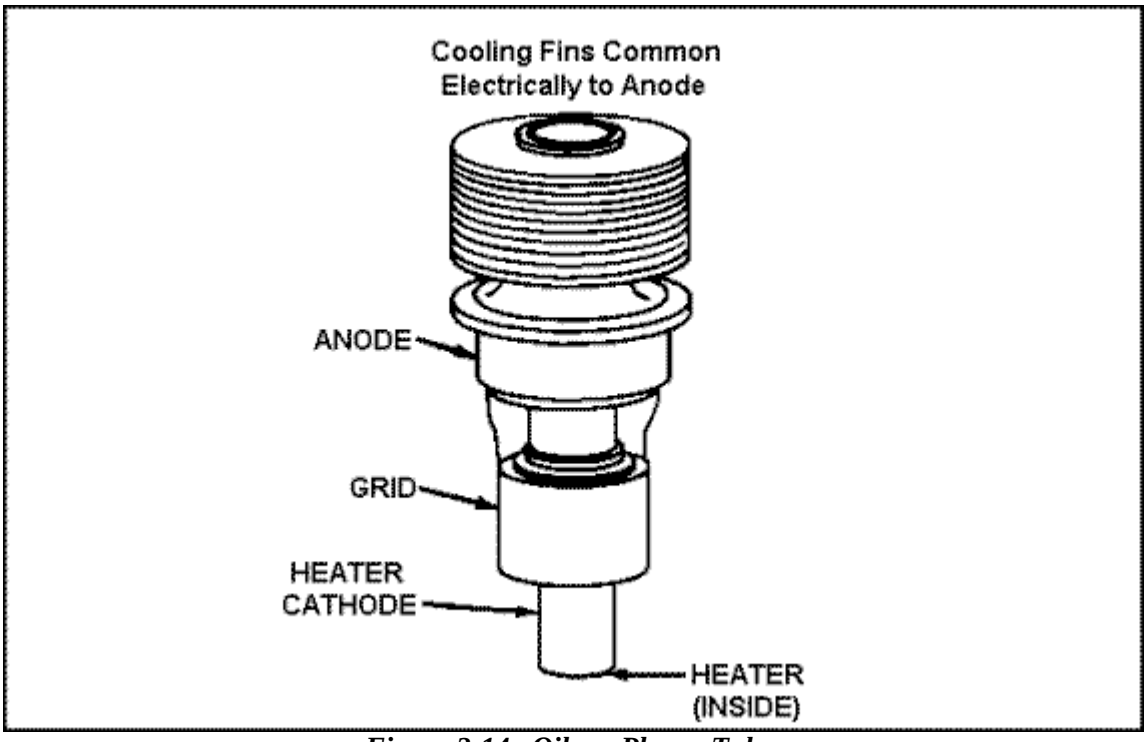

Figure 2-14. Oilcan Planar Tube.

GAS-FILLED TUBES

Great effort is made to produce a vacuum within electron tubes that is as perfect as possible. However, even the best vacuum pumps and getters cannot remove all of the air molecules. However, the chances of an electron hitting an air molecule in a near-perfect vacuum are very slim because of the great distance between the air molecules as compared to the size of the electron. An electron can pass between two molecules of air inside the tube as easily as a pea could pass through a circle having a diameter equal to that of the earth.

In some tubes, the air is removed and replaced with an inert gas at a reduced pressure. The gases used include mercury vapor, neon, argon, and nitrogen. Gas-filled tubes, as they are called, have certain electrical characteristics that are advantageous in some circuits. They are capable of carrying more current than high-vacuum tubes, and they tend to maintain a constant IR drop across their terminals within a limited range of currents. The principle of operation of gas-filled tubes involves the process of ionization.

Electrical Conduction in Gas Diodes

An operating gas-filled tube has molecules, ions, and free electrons present within the envelope. In a gas-filled diode, the electron stream from the hot cathode encounters gas molecules on its way to the plate. When an electron collides with a gas molecule, the energy transmitted by the collision may cause the molecule to release an electron. This second electron then may join the original stream of electrons and is capable of freeing other electrons. This process, which is cumulative, is a form of ionization. The free electrons, greatly increased in quantity by ionization, continue to the plate of the diode. The molecule that has lost an electron is called an ion and bears a

positive charge. The positive drift toward the negative cathode and during their journey attracts additional electrons from the cathode.

The velocity of the electrons traveling toward the plate varies directly with the plate voltage. If the plate voltage is very low, the gas-filled diode acts almost like an ordinary diode except that the electron stream is slowed to a certain extent by the gas molecules. These slower-moving electrons do not have enough energy to cause ionization when they hit the gas atoms. After the plate voltage is raised to the proper level of conduction, the electrons have enough energy to cause ionization when they hit the gas molecules. The plate potential at which ionization occurs is known as the ionization point,or firing potential, of a gas tube. If the plate voltage is reduced after ionization, it can be allowed to go several volts below the firing potential before ionization (and hence high-plate current) will cease. The value of the plate voltage (Ep) at which ionization stops is called the deionization potential, or extinction potential. The firing point is always at a higher plate potential than the deionization point.

Gas Triode

The point at which the gas ionizes can be controlled more accurately by inserting a grid into the gas diode. A negative voltage on the grid can prevent electrons from going to the plate even when the plate voltage is above the normal firing point. If the negative grid voltage is reduced to a point where a few electrons are allowed through the grid, ionization takes place. The grid immediately loses control because the positive ions gather about the grid wires and neutralize the grid's negative charge. The gas triode then acts as a diode. If the grid is made more negative in an effort to control the plate current, the only effect is that more ions collect about the grid wires, and the tube continues to conduct as a diode. Only by removing the plate potential,or reducing it to the point where the electrons do not have enough energy to produce ionization, will tube conduction and the production of the positive ions stop. And only after the production of positive ions is stopped will the grid be able to regain control.

Such gas-filled triodes are known as thyratrons. Thyratrons are used in circuits where current flow in the thyratron's output circuit is possible only when a certain amount of voltage is present on the thyratron's grid. The flow of plate current persists even after the initiating grid voltage is no longer present at the grid, and it can be stopped only by removing or lowering the plate potential. The symbols for the gas-filled diode, the voltage regulator, and the thyratron are the same as that for the high-vacuum tubes except that a dot is placed within the envelope circle to signify the presence of gas. Some examples of gas-filled tube schematic symbols are shown in figure 2-15.

There is one precaution associated with mercury vapor tubes. Mercury vapor is not placed in the tube as a vapor; instead, a small drop of liquid mercury is placed in the tube before it is sealed. When the liquid mercury comes in contact with the hot filament, the mercury vaporizes. To ensure that the mercury has vaporized sufficiently, the filament voltage must be applied to

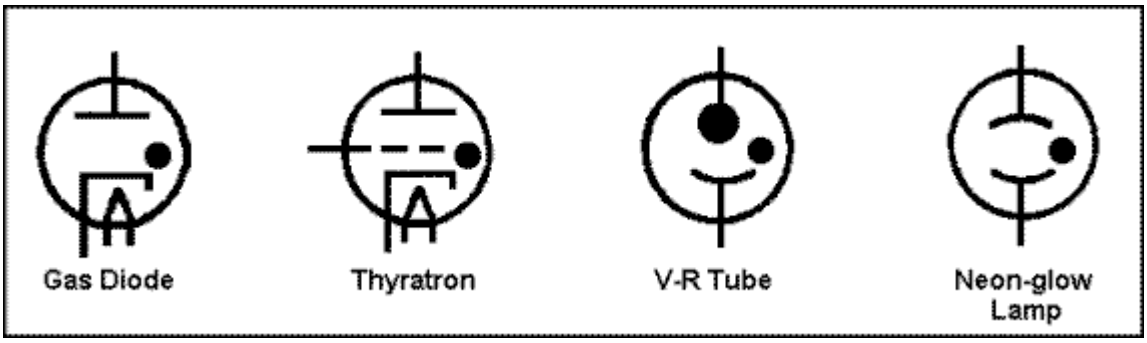

Figure 2-15. Schematic Diagram of Gas-filled Tubes.

mercury vapor tubes for at least 30 seconds before the plate voltage is applied. If vaporization is incomplete, only partial ionization is possible. Under these conditions, the application of plate voltage results in a relatively high voltage drop across the tube (E = I x R), and the positive ions present are accelerated to a high velocity in the direction of the cathode. As the ions strike the cathode they tear away particles of the emitting surface and permanent damage to the cathode and tube usually results. When the mercury is completely vaporized, the action of the gas is such that the voltage drop across the tube can never rise above the ionization potential (about 15 volts). At this low potential, positive ion bombardment of the cathode does not result in damage to the emitting surface.

Generally, when gas-filled tubes are in a state of ionization, they are illuminated internally by a soft, blue glow. This glow is brightest in the space between the electrodes and of lesser intensity throughout the remainder of the tube envelope. This glow is normal and must not be confused with the glow present in high-vacuum tubes when gases are present. A high-vacuum tube with a bluish glow is gassy and should be replaced. The ionization of these gases will distort the output of the tube and may cause the tube to operate with much higher plate current than it can carry safely.

Cold-cathode Tubes

The cold-cathode gas-filled tube differs from the other types of gas-filled tubes in that it lacks filaments. In the tubes covered thus far, thermionic emission was used to send electrons from the cathode to the plate. This conduction of electrons can be caused in another manner. If the potential between the plate and cathode is raised to the point that tube resistance is overcome, current will flow from the cathode whether it is heated or not. In most applications in electronics, this method is not used because it is not as efficient as thermionic emission. There are two applications where cold cathode emission is used. You are already familiar with the first application, although you may not be aware of it. A neon sign is a cold-cathode tube in operation. Thus, the first application of cold-cathode tubes is for visual display. You are also familiar with the reason for this visual display. In FM 11-60 (Communications--Electronics Fundamentals: Basic Principles, Direct Current) it is explained that when energy is fed into an atom (neon in this case), electrons are moved or promoted to higher orbits. When they fall back, they release the energy that originally lifted them to their higher orbits. This

energy is in the form of light. Cold-cathode tubes are also used as voltage regulators. A cold-cathode tube has the ability to maintain a constant voltage drop across the tube despite changes of current flow through the tube. The tube does this by changing resistance as current flow varies.

Figure 2-16 shows a cold-cathode tube connected to a variable voltage source. The variable resistor rkp does not exist as a physical component but is used to represent the resistance between the cathode and plate. Most cold cathode tubes have a firing point (ionizing voltage) at about 115 volts. Thus, the tube in view A of the figure is below the firing point. Because the tube lacks thermionic emission capabilities, no current will flow, and the tube will have a resistance (rkp) near infinity. The potential difference between the plate and ground under these conditions will be equal to the source ($E_{bb)}$ voltage, as shown on the voltmeter.

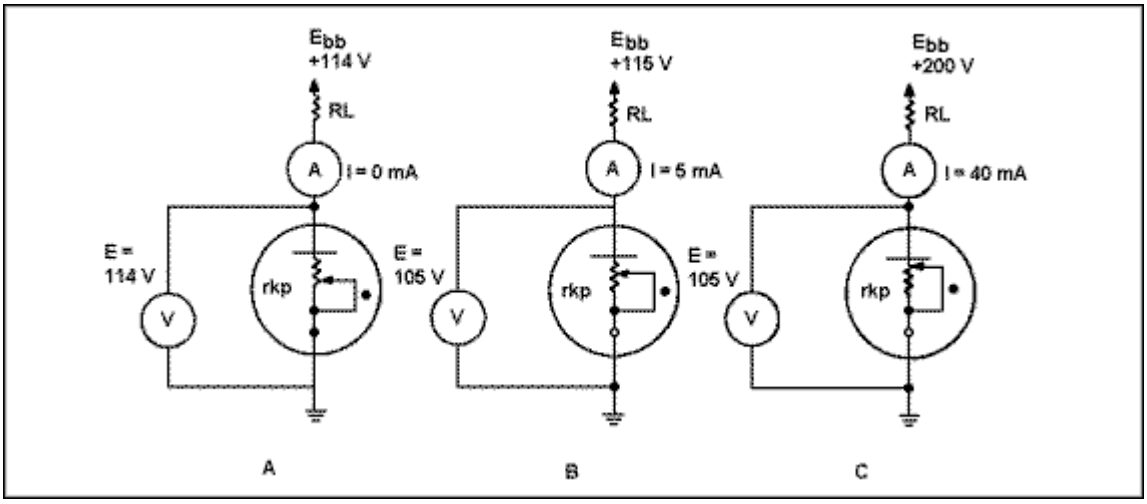

Figure 2-16. Cold-cathode Tube Operation.

In view B the source voltage has been raised to the firing point of 115 volts. This causes the gas to ionize, and 5 milliamperes of current will flow through the tube. Because the tube represents a resistance (rkp), voltage will be dropped across the tube, in this case 105 volts. The plate-load resistor (R_L) will drop the remaining 10 volts. The resistance of the tube at this time will be equal to:

$$rkp = \frac{E}{I}$$

$$rkp = \frac{105 \text{ volts}}{.005 \text{ ampere}}$$

$$rkp = 21 \text{ k}\Omega$$

In view C the source voltage has been raised to 200 volts. This will cause more gas in the tube to ionize, and 40 milliamperes of current to flow through the tube. The increased ionization will lower the resistance of the

tube (rkp). Thus, the tube will still drop 105 volts. The tube's resistance (rkp) at this time will be equal to:

$$rkp = \frac{E}{I}$$

$$rkp = \frac{105 \text{ volts}}{40 \text{ milliamperes}}$$

$$rkp = 2.625 \text{ k } \Omega$$

Increasing the current flow will cause more ionization in the tube and a corresponding decrease in the tube's resistance. Because of this, the tube will always have a constant voltage drop between its plate and cathode throughout its operating range.

CATHODE RAY TUBES

Cathode ray tubes (CRTs) can be considered as the heart of the many types of electronic equipment that give visual information. They have one function that cannot be duplicated by any other tube or transistor: they have the ability to convert electronic signals to visual displays, such as pictures, radar sweeps, or electronic waveforms. Figure 2-17 shows a cutaway view of a typical CRT.

All CRTs have three main elements: an electron gun, a deflection system, and a screen. The electron gun provides an electron beam, which is a highly concentrated stream of electrons. The deflection system positions the electron beam on the screen. The screen displays a small spot of light at the point where the electron beam strikes it.

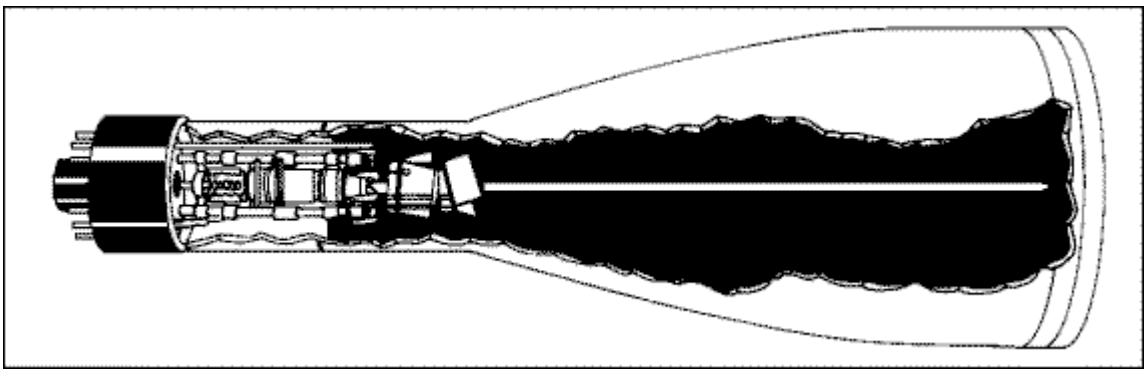

Figure 2-17. Cutaway View of a Typical CRT.

Electron Gun

The electron gun is roughly equivalent to the cathodes of conventional tubes. The cathode of the electron gun in the CRT is required not only to emit electrons but also to concentrate emitted electrons into a tight beam. In the electron tubes that you have studied, the cathode was cylindrical and emitted

electrons in all directions along its entire length. This type of cathode is not suitable for producing a highly concentrated electron beam. The cathode of the CRT consists of a small diameter nickel cap. The closed end of the cap is coated with emitting material. This is shown in figure 2-18. Because of this type of construction, electrons can be emitted in only one direction. Note that the emitted electrons shown in figure 2-18 are leaving the cathode at different angles. If these electrons were allowed to strike the screen, the whole screen would glow. Since the purpose of the CRT is to concentrate the electrons into a tight beam, a special grid must be used. This special grid is in the form of a solid metal cap with a small hole in the center. The grid is placed over the emitting surface of the cathode and charged negatively in relation to the cathode. The dotted lines represent electrostatic field between the grid and the cathode as shown in figure 2-19. Since all emitted electrons leave the cathode (point C), their paths can be identified. An electron attempting to travel from point C to point B (downward) will instead follow the path from point C to point E to point P. Consider an electron leaving point C in the direction of point A (upward). Its path will be curved from point C to point P by electrostatic repulsion. These curving electron paths are due to the negative potential of the grid coupled with the high positive potential of the anode. The potential of the anode attracts electrons out of the cathode grid area past point P toward the screen. The grid potential may be varied to control the number of electrons allowed to go through the control grid opening. Since the brightness or intensity of the display depends on the number of electrons that strike the screen, the control grid is used to control the brightness of the CRT.

Brightness control is the name given to the potentiometer used to vary the potential applied to the control grid. The control grid actually serves as an electronic lens. It is this electronic lens that you adjust when you turn up the brightness control on a TV set. The effect of the grid is to focus the electron beam at point P in figure 2-19. After passing point P, the electrons start to spread out, or diverge, again. Therefore, it becomes necessary to provide some additional focusing to force the electrons into a tight beam again. This is done by two additional positively charged electrodes as shown in figure 2-20. The first electrode is commonly called the focusing anode. Generally, the focusing anode is charged a few hundred volts positive in respect to the cathode. Electrons emitted by the cathode are attracted to the focusing

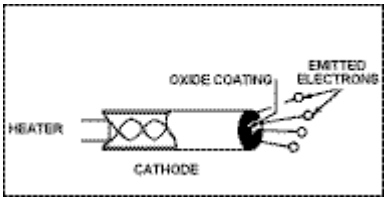

Figure 2-18. CRT Cathode.

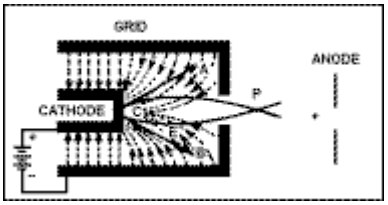

Figure 2-19. Operation of CRT Grid.

anode. This is the reason that they travel through the small hole in the grid. The second electrode, called the accelerating anode, is charged several thousand volts positive in relation to the cathode. Any electrons approaching the focusing anode will feel the larger electrostatic pull of the accelerating anode, will be bent through the opening in the focusing anode, and will travel into the area labeled D. Because the accelerating anode is cylindrical in shape, the electrostatic field radiating from it is equal in all directions. Thus, an electron is pulled in all directions at once, forcing the electron to travel down the center of the tube. Then, the electron is accelerated into the accelerating anode. Once it passes the midpoint (point E), it feels the electrostatic attraction from the front wall of the accelerating anode, which causes it to move faster toward the front. Once it reaches point F, equal electrostatic attraction on either side of the opening squeezes it through the small opening in the front of the anode. From there, it is joined by millions of other electrons and travels in a tight beam until it strikes the screen (point S).

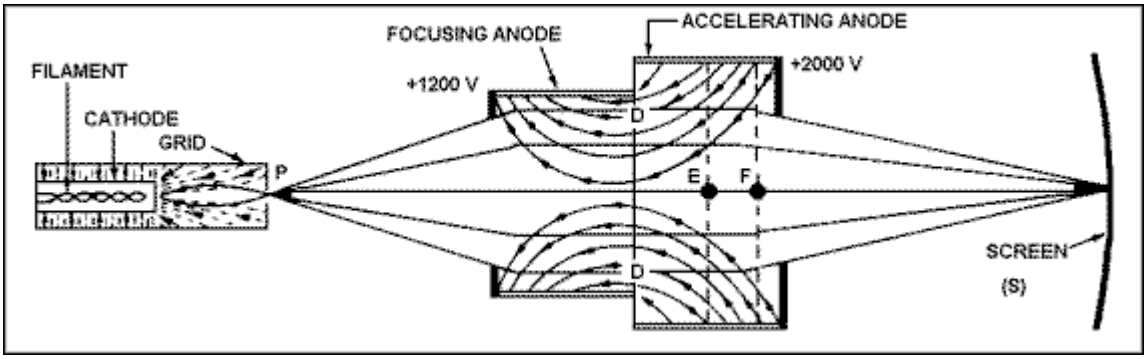

Figure 2-20. Electron Beam Formation in a CRT

CRT Screen

The inside of the large end of a CRT is coated with a fluorescent material that gives off light when struck by electrons. This coating is necessary because the electron beam itself is invisible. The material used to convert the electrons' energy into visible light is a phosphor. Many different types of phosphor materials are used to provide different-colored displays and displays that have different lengths of persistence (duration of display).

In one way, the CRT screen is similar to a tetrode vacuum tube. Both suffer from the effects of secondary emission. In order to reach the screen, electrons from the cathode are accelerated to relatively high velocities. When these electrons strike the screen, they dislodge other electrons from the material of the screen. If these secondary emission electrons are allowed to accumulate, they will form a negatively charged barrier between the screen and the electron. The result is a distorted image on the CRT screen. The method used to control secondary emission, a suppressor grid, is not practical in CRTs. Instead, a special coating called an aquadag coating is applied to the

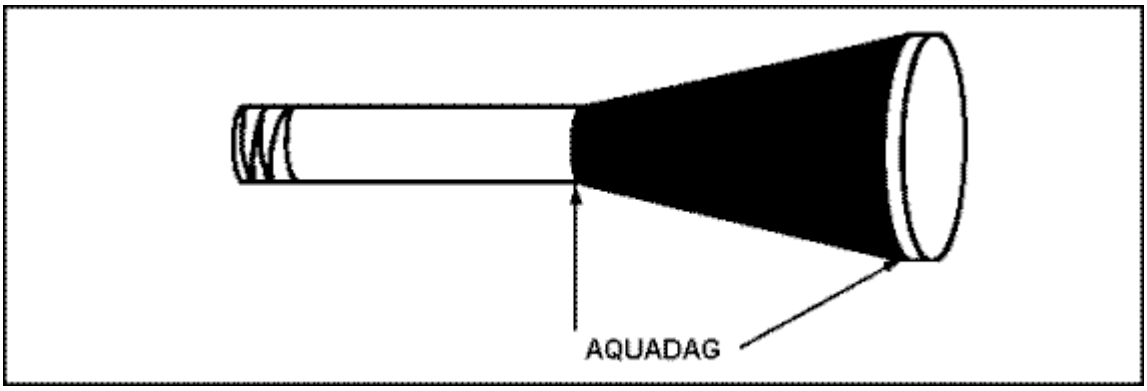

Figure 2-21. Aquadag Coating in a CRT

inside of the tube as shown in figure 2-21. This coating is composed of a conductive material, such as graphite, and has the same high-positive potential applied to it that is applied to the accelerating anode. This allows the aquadag coating to perform two functions. The first is the elimination of secondary emitted electrons. This is done by attracting the negatively charged electrons to the positive aquadag coating and removing them by the positive voltage source. Second, because the aquadag coating is operated at a high-positive potential and is in front of the accelerating anode, it aids in the acceleration of electrons toward the screen.

Deflection System

Shown in figure 2-22 is a CRT screen containing a bright spot in its center. Having watched TV, you know that a TV picture consists of more than just a bright spot in the center of the picture tube. Obviously, something is necessary to produce the picture. For the CRT to work properly, the spot must be moved to various positions on the screen. This process is called deflection. In a TV set, for example, the spot is moved horizontally across the CRT face to form a series of tightly packed lines. As each line is displayed, or traced, the electron beam is moved vertically to trace the next line as shown in figure 223. This process starts at the top of the tube and ends when the last line is traced at the bottom of the CRT screen. Because the beam is swept very fast across the CRT and the phosphor continues to glow for a short time after the beam has moved on, you do not see a series of lines but a continuous picture.

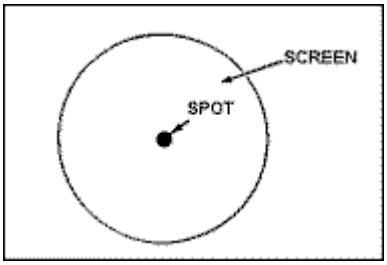

Figure 2-22. Impact of an Electron Beam on a CRT Screen.

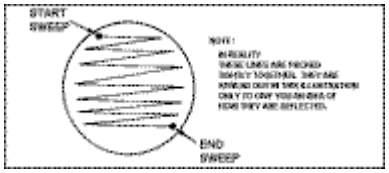

Figure 2-23. Deflection of an Electron Beam Across a TV Screen.

The CRT makes up the heart of the technician's major tool, the oscilloscope. The unique function of a CRT is to convert electronic (and electrical) signals to a visual display. This function of a CRT is used by the oscilloscope to show the waveform of any electronic signal. For this reason, the type of deflection used in oscilloscopes will be discussed.

There are two ways to move an electron (and thus an electron beam). An electron may be moved either by a magnetic field or an electrostatic field. Because of this, there are three possible ways to move or deflect an electron beam in a CRT: magnetically, electromagnetically, and electrostatically. Each type is used in electronics. In general, though, electrostatic and electromanetic deflection are the types used most often. TV sets, for example, use electromagnetic deflection while much of the test equipment in the Navy uses electrostatic deflection.

Electrostatic deflection uses principles you are already familiar with: namely, opposites attract and likes repel. Figure 2-24, view A, shows an electron traveling between two charged plates, H1 and H2. Before the electron reaches the charged plates, called deflection plates, its flight path is toward the center of the screen. In view b, the electron has reached the area of the deflection plates and is attracted toward the positive plate H2 while being repelled from the negative plate H1. As a result, the electron is deflected to the right of the inside of the screen. The viewer (on the opposite side of the CRT screen) sees the spot of light deflected to the left of the CRT face.

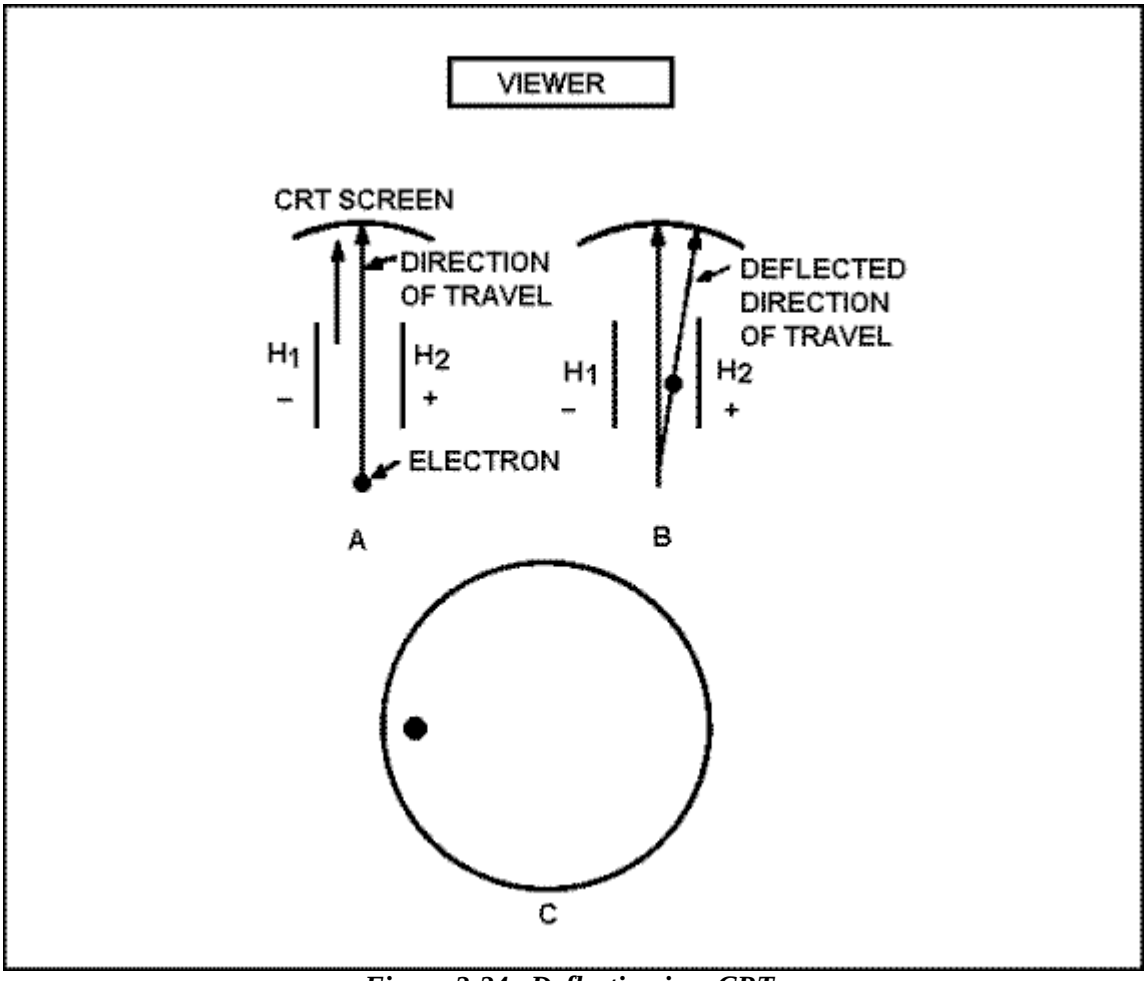

Figure 2-24. Deflection in a CRT.

A spot of light on the left-hand side of the CRT screen, however, is no more useful than a spot of light in the center of the screen. To be useful, this spot will have to be converted to a bright line, called a sweep, across the face of the CRT screen. The manner in which this is done will be explained using figure 2-25. In view A five electrons are emitted in sequence, 1 through 5, by the electron gun. The left deflection plate (H1) has a large positive potential on it, while the right plate (H2) has a large negative potential on it. Thus, when electron 1 reaches the area of the deflection plates, it is attracted to the left plate while being repelled from the right plate. In view B electron 2 has reached the area of the deflection plates. However, before it arrives, R1 and R2 are adjusted to make the left plate less positive and the right plate less negative. Electron 2 will be deflected to the left but not as much as electron 1. In view C electron 3 has reached the area of the deflection plates. Before it got there, R1 and R2 were adjusted to the midpoint. As a result, both plates have zero volts applied to them. Electron 3 is not deflected and simply travels to the center of the CRT screen. In view D electron 4 has reached the area of the deflection plates. Note that R1 and R2 have been adjusted to make the left plate negative and the right plate positive. As a result, electron 4 is deflected to the right. Finally, in view C the left plate is at its maximum positive value. Electron 5 is deflected to the extreme right. What you see when you are facing the CRT is a bright luminous line as shown in view F. While this description deals with only five electrons, in reality the horizontal line across a CRT face is composed of millions of electrons. Instead of five bright spots in a line, only a solid bright line is seen.

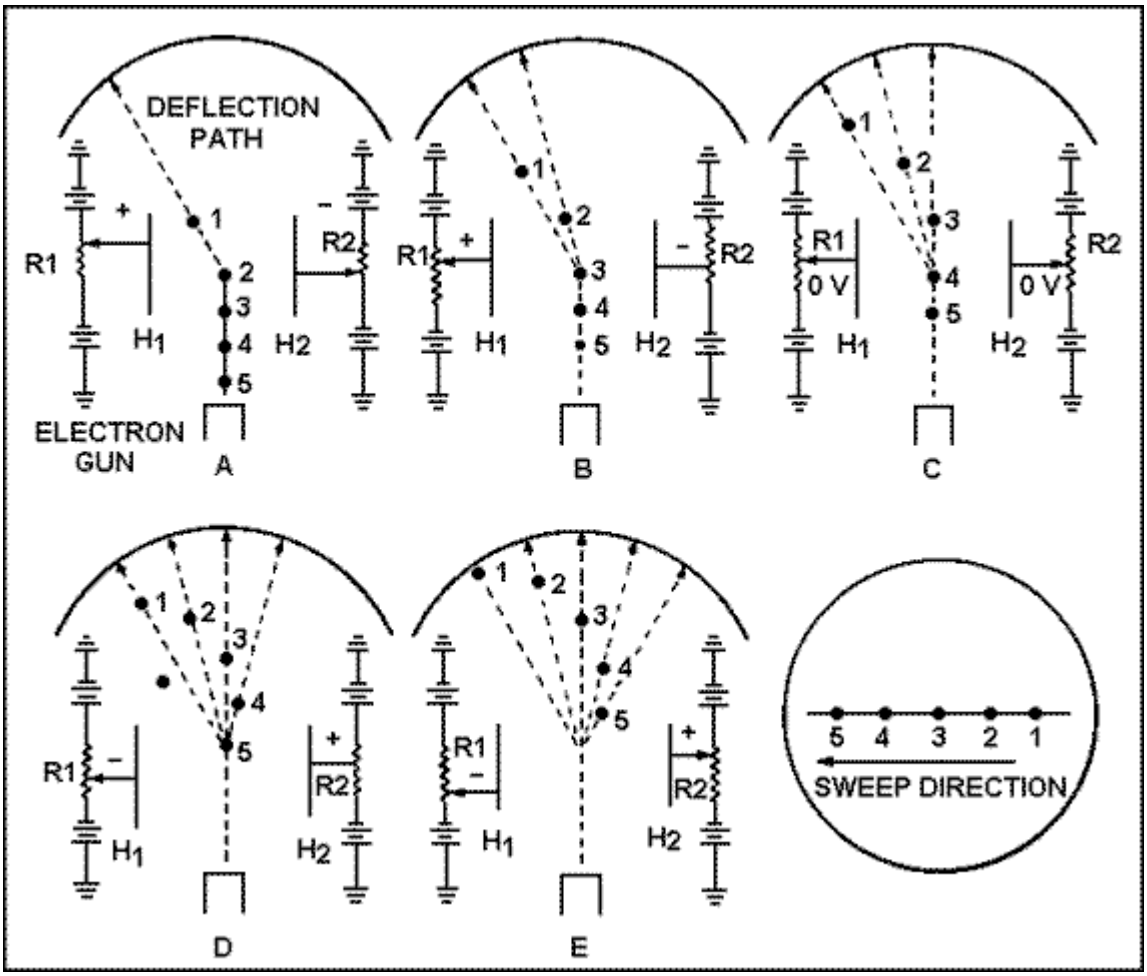

Figure 2-25. Horizontal Deflection.

In summary, the horizontal line displayed on a CRT or on the face of a television tube is made by sweeping a stream of electrons rapidly across the face of the CRT. This sweeping action, or scanning, is performed by rapidly varying the voltage potential on the deflection plates as the electron stream passes.

As mentioned earlier, a CRT can be used to plot graphically and visually an electronic signal such as a sine wave. This is done by using a second set of deflection plates called vertical deflection plates. Figure 2-26 shows the front view (facing the screen) of a CRT, looking back into the tube at the deflection plates. In normal usage, the horizontal plates sweep a straight line of electrons across the screen while the signal to be displayed is applied to the vertical deflection plates. A circuit of this type is shown in figure 2-27. This figure will be used to explain how a sine wave is displayed.

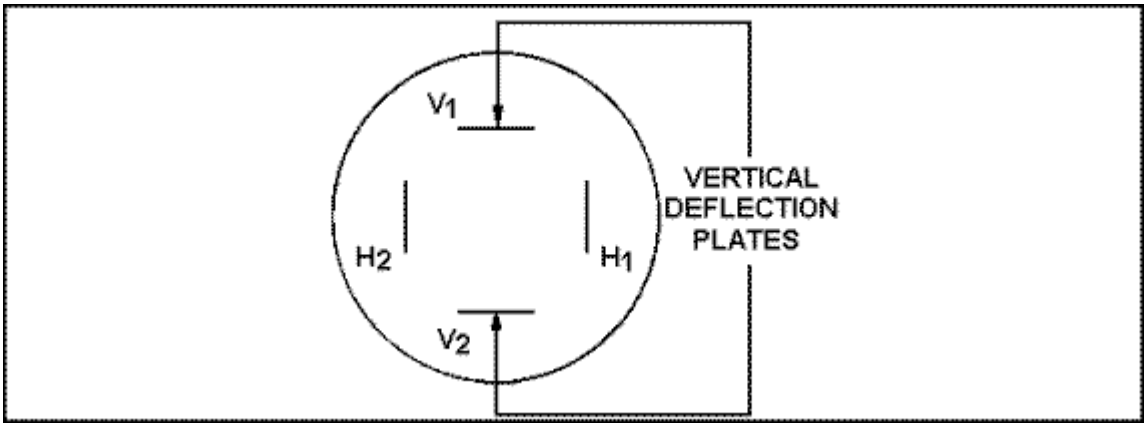

Figure 2-26. Arrangement of Deflection Plates in a CRT, Front View.

View A of figure 2-27 shows a box on the left of the CRT labeled horizontal deflection circuits. This box is an electronic circuit that will duplicate the actions of R1 and R2 used earlier in making up a horizontal line. Note T1. The output of this transformer is applied to the vertical deflection plates. The signals applied to the vertical plates are 180 degrees out of phase with each other. Thus, when one plate is attracting the electron beam, the other is repelling the electron beam. Because it is only necessary to know what happens inside the CRT, this circuitry will be eliminated and only the CRT and its deflection plates will be shown, as in view B.

In view C the sine wave in the center of the screen is the signal that will be displayed as a result of the two 180-degree out-of-phase sine waves applied to the vertical deflection plates. The five spots on the center sine wave represent the five electrons used to explain horizontal deflection, only now these electrons will be deflected both vertically and horizontally. The time lines, T1 through T5, represent the time when each like-numbered electron reaches the area of the deflection plates. Note that from T1 to T5, the electron beam will be continuously moved from right to left.

At time 1 (T1), the sine waves applied to both vertical deflection plates are at their null points, or zero volts. As a result, electron 1 is not vertically deflected and strikes the CRT screen at its vertical center. At time 2 (T2), the

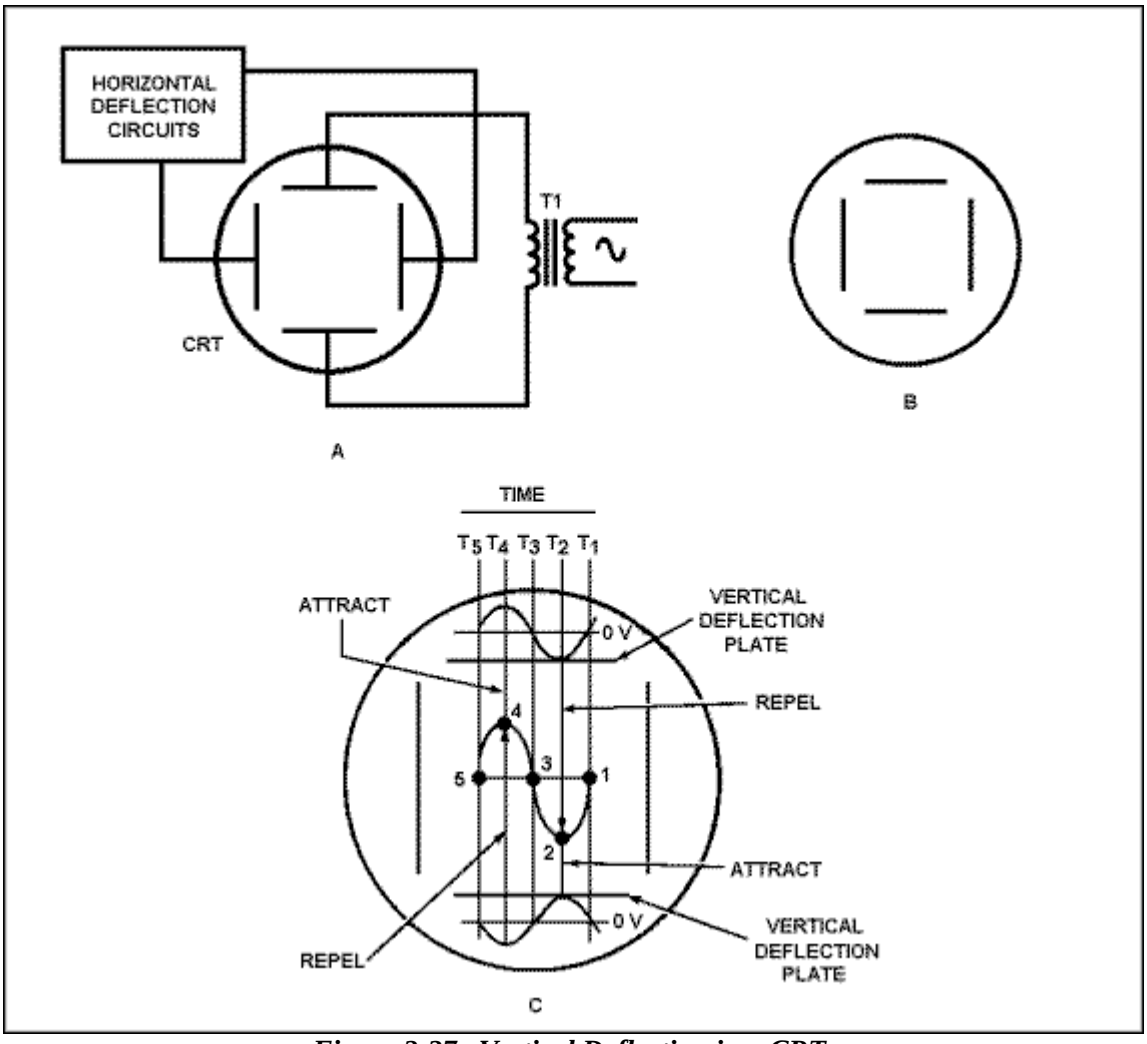

Figure 2-27. Vertical Deflection in a CRT.

sine wave applied to the top plate is at its maximum negative value. This repels electron 2 toward the bottom of the CRT. At the same time, the sine wave applied to the bottom plate is at the most positive value, which attracts electron 2 even further toward the bottom of the CRT. Note that the beam is also being moved to the left. As a result, electron 2 strikes the CRT face to the left and below electron 1. At time 3 (T3), both sine waves applied to the vertical deflection plates are again at the null point, or zero volts. Therefore, there is no vertical deflection, and electron 3 strikes the CRT face in the center of the vertical axis. Because the electron beam is still moving horizontally, electron 3 will appear to the left and above electron 2. At time 4 (T4), the sine wave applied to the top vertical deflection plate is at its maximum positive value. This attracts electron 4 toward the top deflection plate.

The upward deflection of electron 4 is increased by the negative-going sine wave (at time 4) applied to the bottom deflection plate. This negative voltage repels electron 4 upward. Thus, electron 4 strikes the CRT face to the left and above electron 3. Finally, at time 5 (T5), input electron 5 is not deflected vertically, only horizontally. (The beam is horizontal and is continually moving from right to left.) While this discussion is only concerned with five electrons, vertical scanning, or deflection, involves millions of electrons in a continuous electron beam. Instead of seeing five spots on the CRT screen, you actually see a visual presentation of the sine wave input.

There are two reasons for emphasizing the importance of CRTs. First, the field of electronics is in a constant state of evolution. Transistors are rapidly replacing vacuum tubes and are, at the same time, being replaced by integrated circuits (IC). Electronics equipment follows this evolution, from transistors to IC chips. Of all the tubes discussed in this subcourse, the CRT is the least likely to be replaced in the near future. The second reason is that while the CRT has a unique ability, it operates exactly like all the tubes previously discussed. Figure 2-28 shows both a schematic diagram and a pictorial representation of a CRT. Each element is identified by a circled number. Each number (element) will be discussed relative to its function in a CRT and its similarity to elements in conventional tubes.

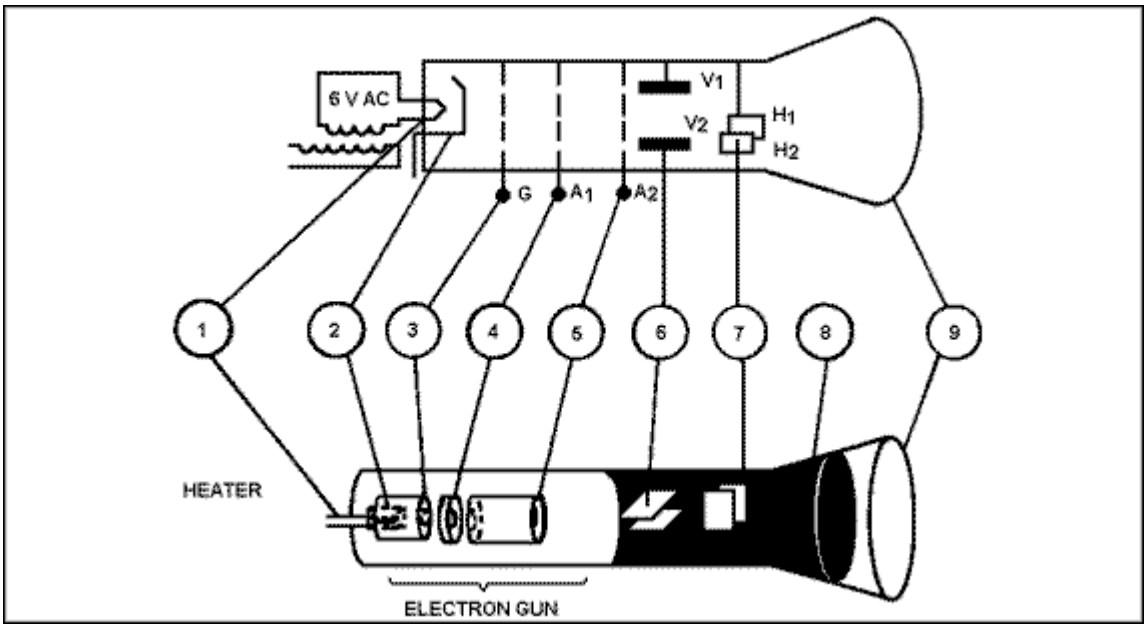

Figure 2-28. Summary of CRT

The heater (1) serves as the source of heat for the cathode in both the CRT and indirectly heated tubes. The cathode (2) serves as the source of thermionically emitted electrons in both the CRT and conventional tubes. The major difference is that in the CRT the cathode is circular in shape, and the outer surface is coated to ensure that electron emission is roughly unidirectional.

In both the CRT and conventional vacuum tubes, the control grid (3) controls the number of electrons that will be fired across the gap. The major difference is in the physical construction. Conventional tubes employ a wiremesh ladder type of grid, while the CRT employs a cap-like grid.

In the CRT the focusing anode (4) serves a dual purpose: attracting electrons from the area of the control grid and focusing the electrons into a beam. Its function of attracting electrons from the area of the grid is similar to the action of the plate in a conventional tube. The focusing action of the anode is similar to that performed by the beam-forming tetrode. However, beam-forming plates are negatively charged and repel electrons into electron sheets, while the focusing anode is positively charged and attracts electrons into a beam.

In the CRT the accelerating anode (5) is used to accelerate electrons toward the front of the tube. Its action is similar to the screen grid of tetrodes and pentodes. Note that while the screen in conventional tubes accelerates electrons toward the plate, its primary purpose is to reduce interelectrode capacitance, not accelerate electrons.

In the CRT vertical deflection plates (6) move the electron beam up and down the screen. When used in test equipment, the input signal is usually applied to these plates. While no equivalent element is found in conventional tubes, the principle employed (electrostatic attraction and repulsion) forms the heart of all vacuum tube operation.

In the CRT horizontal deflection plates (7) move the electron beam by electrostatic attraction and repulsion, horizontally across the CRT screen. In most equipment employing the CRT, including television sets, electronic signals are applied to these plates to trace or paint a horizontal line.

In the CRT the aquadag coating (8) performs the same function as the suppressor grid in conventional tubes: it eliminates the effects of secondary emission. In conventional tubes, the suppressor grid is negatively charged and repels secondary emission electrons back to the plate. In the CRT the aquadag is positively charged and attracts secondary emission electrons away from the screen.

The screen (9), also called the face, is a unique element of the CRT. When struck by electrons, the phosphor coating becomes luminous, or glows, thus enabling the tube to present electronic signals visually.

From this comparison of the CRT and other types of electron tubes, one fact should be clear. Almost all tubes, no matter what their function, operate on two principles: electrostatic attraction and repulsion and thermionic emission.

SAFETY

There are certain safety precautions you should follow when you are working with or handling the special tubes covered in this subcourse. These tubes and their associated precautions are discussed below.

Electron Tubes

The average electron tube is a rugged device capable of withstanding the shocks and knocks of everyday usage and handling. However, they are not indestructible. Most electron tubes contain a near vacuum enclosed by a glass envelope. Because of this, the glass is under constant stress from atmospheric pressure. Any undue stress, such as striking the envelope against a hard surface, may cause an envelope to shatter, resulting in an implosion. An implosion is just the opposite of an explosion. When the glass envelope of an electron tube shatters, the outside atmosphere rushes into the tube to fill the vacuum. As the air rushes into the tube, it carries glass fragments of the envelope with it. Once these fragments reach the center of the tube, they then move outward with considerable velocity. The result is similar to an explosion in that the immediate area surrounding the electron tube is filled with fast-moving glass fragments. Any nearby object, including the technician, becomes a target for these glass fragments. For this reason all electron tubes should be handled with care.

Cathode Ray Tubes

Due to the small size of most electron tubes, the possibility of hazard is usually very small. There are two exceptions to this: CRTs and radioactive tubes. The glass envelope of a CRT encloses a high degree of vacuum. Because of its large volume and surface area, the force exerted on a CRT by atmospheric pressure is considerable. The total force on a 10-inch CRT may exceed 4,000 pounds. Over 1,000 pounds is exerted on the CRT face alone.

When a CRT is broken, through mishandling, a large implosion usually occurs. Almost two tons of force hurl glass fragments toward the center of the tube. At the same time, the electron gun is normally thrown forward inside the tube. The face, because of its size, tends to move very slowly toward the center of the tube. This presents one of the main hazards of a broken CRT. The electron gun passes through the center of the tube with considerable force. It continues until it strikes the CRT face. The impact from the electron gun normally breaks the CRT face into many small fragments, which are hurled outward. The face is coated with a chemical coating that is extremely toxic. If you experience an accidental implosion of a CRT and are nicked by one of these fragments, seek immediate medical aid. Improper handling of a CRT can be very dangerous.

The CRT is, in essence, a tiny fragmentation bomb. The major difference between a CRT and a bomb is that a bomb is designed to explode, while a CRT is not. As long as a CRT is properly handled, it represents no danger to you. Only when it is mishandled, do you risk the danger of being pelted with an electron gun and toxic glass fragments. When handling a CRT, you should take the following precautions:

- Avoid scratching or striking the surface of a CRT.

- Do not use excessive force when removing or replacing a CRT in its deflection yoke or its socket.

- Do not try to remove an electromagnetic type of CRT from its anode connector (hole).
- Never hold a CRT by its neck.
- Always set a CRT with its face down on a thick piece of felt, rubber, or smooth cloth.
- Always handle a CRT gently. Rough handling or a sharp blow on the service bench can displace the electrodes within the tube, causing faulty operation.
- Wear safety glasses and protective gloves.

Always render a CRT harmless before disposing of it. Place the CRT that is to be discarded face down in an empty carton and cover its side and back with protective material. Carefully break off the plastic locating pin from the base (see figure 2-29). This can be done by crushing the locating pin with a pair of pliers or vice grips. Brush the broken plastic from the pin off the CRT base. Once you have done this, look into the hole in the base where the locator pin was. You will see the glass extension of the CRT called the vacuum seal. Grasp the vacuum seal near the end with the pliers and crush it. The vacuum seal can be crushed without shattering the tube. Once the seal has been crushed, air will rush into the tube and eliminate the vacuum.

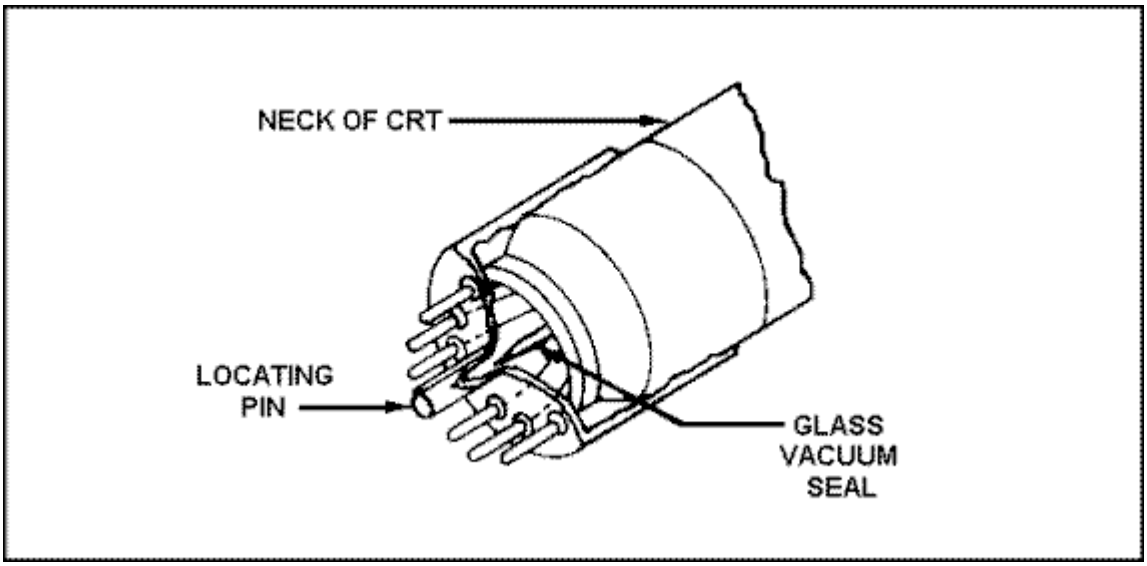

Figure 2-29. Cathode Ray Tube Base Structure.

Conventional Tubes

While conventional tubes present few safety problems beyond broken glass and the possibility of cutting yourself, there is one precaution you must know: electron tubes are hot. The filaments of some tubes may be operated at several thousand degrees. As a result, the envelopes can become very hot. When working on electron tube equipment, always de-energize the equipment and allow the tubes sufficient time to cool before removing them. If this is impossible, use special tube pullers that are stocked for this purpose. Never attempt to remove a hot tube from its socket with your bare fingers.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. How is conduction stopped in a thyratron tube?

   a. By making the control grid negative. b. By removing the plate potential.

   c. By making the control positive.

   d. By increasing the cathode voltage.

2. Which of the tubes shown below is a gas-filled thyratron?

Figure 2-30.

3 What are the beam forming plates in a beam power tube connected to?

   a Cathode.

   b Plate.

   c Control grid.

   d Screen grid.

4 What is the difference in a power pentode and a conventional pentode?

   a The grids in a power pentode are staggered.

   b The grids in a power pentode are in line.

   c The grids in a power pentode are in line except for the screen grid.

   d The grids in a power pentode are in line except for the suppressor grid.

5 To which element(s) of a CRT is the signal that moves the electron beam up and down applied?

a Vertical deflection plates.

b Horizontal deflection plates.

c Control grid.

d Cathode.

6 Which of the following statements is true concerning a cold-cathode tube?

a It maintains a constant voltage drop despite current changes.

b It maintains a constant resistance despite current changes.

c It maintains a constant current despite voltage changes.

d It maintains a constant current despite resistance changes.

7 What is meant by the term multielectrode tube?

a It has more than one tube enclosed in a single envelope.

b It has more than three grids.

c It has less than three grids.

d It has three grids.

8 What is the firing potential of a gas-filled tube?

a Cathode potential at which ionization occurs

b Cathode potential at which deionization occurs.

c Plate potential at which ionization occurs.

d Plate potential at which deionization occurs.

9 What is another name for a variable mu tube?

a Beam power tube.

b Sharp cutoff tube.

c Remote cutoff tube.

d Power pentode tube.

10 What element in a CRT is connected to the brightness control?

a Cathode.

b Control grid.

c Focusing anode.

d Accelerating anode.

11 What type of UHF tube was developed to handle large amounts of power?

a Planar tube.

b Acorn tube.

c Doorknob tube.

d Beam power tube.

12 What is the name of the tube shown below?

a Multiunit tube.

b Pentode tube.

c Pentagrid tube.

d Tetrode tube.

IMAGE: Figure 2-31.

13 What are the three main elements of a CRT?

a Electron gun, screen, and aquadag coating.

b Electron gun, deflection system, and aquadag coating.

c Electron gun, deflection system, and screen.

d Deflection system, screen, and aquadag coating.

14 What is one advantage that a gas-filled tube has over a conventional electron tube?

a It amplifies better.

b It can carry more current.

c It acts like a fixed resistor.

d It doesn't need a cathode.

15 Variable mu tubes were developed because some tubes are required to amplify which of the following?

a Relatively large input signals with distortion.

b Relatively small input signals with distortion.

c Relatively large input signals without distortion.

d Relatively small input signals without distortion.

16 What is the only difference between a remote cutoff tube and a sharp cutoff tube?

a Plate size.

b Control grid wire spacing.

c Screen grid wire spacing.

d Suppressor grid wire spacing.

17 What is the purpose of the horizontal deflection plates in a CRT using electrostatic deflection?

a To cause the electron beam to sweep up on the screen.

b To cause the electron beam to sweep down on the screen.

c To cause the electron beam to sweep across the screen.

d To cause the electron beam to sweep up and down the screen.

18 What is meant by the term multiunit tube?

a It has more than one tube enclosed in a single envelope.

b It has more than three grids.

c It has less than three grids.

d It has three grids.

19 What is the function of the grid in a thyratron tube?

a To initiate tube conduction.

b To control current flow.

c To drive the tube to cutoff.

d To control plate current.

20 What is done to UHF tubes in order to reduce the effects of transit time?

a Large electrodes are placed close together.

b Small electrodes are placed far apart.

c Large electrodes are placed far apart.

d Small electrodes are placed close together.

21 How does a cold-cathode gas-filled tube differ from other gas-filled tubes?

a It uses a very low-filament voltage.

b It uses a grid to stop conduction.

c It does not have filaments.

d It does not use a plate.

22 What is the function of the aquadag coating in a CRT?

a To slow down the electrons hitting the screen.

b To deflect the electron beam.

c To eliminate secondary emission.

d To rejuvenate the phosphors.

23 What is the function of the focusing anode in a CRT?

a To attract electrons from the control grid only.

b To focus electrons into a beam and attract electrons from the grid.

c To focus electrons into a beam and accelerate them.

d To attract electrons from the grid and accelerate them.

24 What is the range of sharp cutoff tubes limited by?

a Bias voltage only.

b Bias voltage and distortion.

c Tube characteristics only.

d Bias voltage and tube characteristics.

25 What type of tube would be most suitable for low distortion amplifiers that use large signal inputs?

a Variable mu tubes.

b Beam power tubes.

c Conventional tubes.

d Power pentode tubes.

Lesson 3
POWER SUPPLIES

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to identify the sections of a power supply and state the purpose of each; describe the operation of a power supply from both a whole unit standpoint and from a subunit standpoint; describe the purpose of the types of rectifier and filter circuits; describe the operation of the voltage and current regulators; trace the flow of ac and dc in a power supply, beginning from the ac input to the dc output on a schematic diagram; identify faulty components through visual checks; identify problems within specific areas of a power supply by using a logical isolation method of troubleshooting; and describe safety precautions to be taken when working with electronic power supplies.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 2, 4, 5, 6, and 7.

BASIC POWER SUPPLY

Figure 3-1 shows the block diagram of the basic power supply. Most power supplies are made up of four basic sections: a transformer, a rectifier, a filter, and a regulator. The transformer serves two primary purposes: to step up or step down the input line voltage to the desired level and to couple this voltage to the rectifier section. The rectifier section is used to convert the ac signal to a pulsating dc voltage. However, the pulsating dc voltage is not desirable. For this reason, a filter section is used to convert the pulsating dc voltage to a filtered dc voltage. The regulator maintains the output of the power supply at a constant level in spite of large changes in load current or in input line voltage. Depending upon the design of the equipment, the output of the regulator will maintain a constant dc voltage within certain limits.

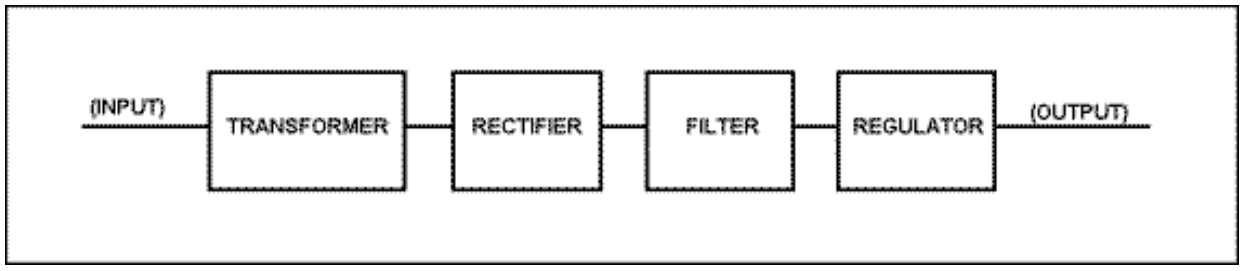

Figure 3-1. Block Diagram of a Basic Power Supply.

In figure 3-2, the input signal of 120 volts ac is applied to the primary of the transformer, which has a turns ratio of 1:3. By multiplying the input voltage by the ratio of turns in the primary windings to turns in the secondary windings in a step-up transformer, the output can be calculated. Therefore, 120 volts ac x 3 = 360 volts ac at the output. Because the diode tube in the rectisection conducts only on the positive alternation of the input signal, the output will be only half of the input signal, or 180 volts of pulsating dc to the filter. The filter section contains a network of resistors, capacitors, or inductors that control the rise and fall time of the varying signal so that the signal remains at a more constant dc level. The output of the filter is at a 180-volt dc level with an ac ripple voltage riding on it. (Ripple voltage is a small ac voltage riding at some dc voltage level. Normally, ripple voltage is an unwanted ac voltage created by the filter section of a power supply.) This signal now goes to the regulator where it is maintained at approximately 180 volts dc to the load.

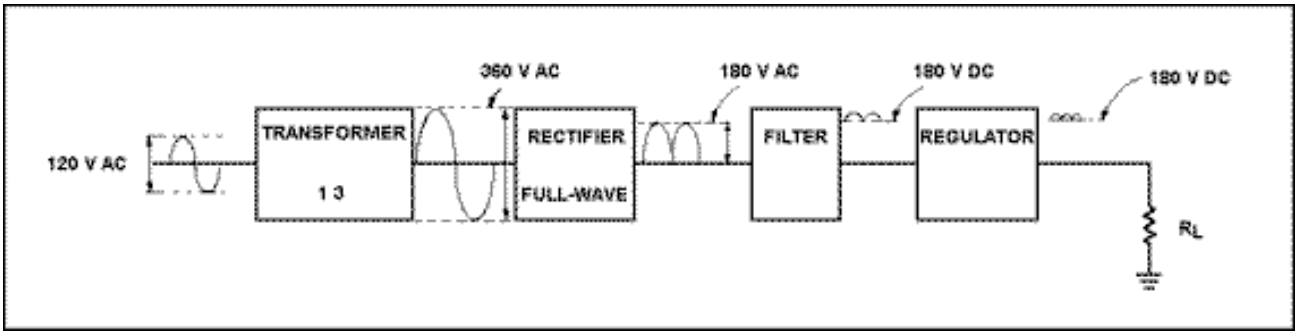

Figure 3-2. Block Diagram of a Power Supply.

Transformers

In addition to its two primary purposes, the transformer also couples the input ac signal to the power supply and isolates the electronic power supply from the external power source and either steps up or steps down the ac voltage to the desired level. Also, most input transformers have separate stepdown windings to supply filament voltages to both power supply tubes and the tubes in the external equipment (load). Such a transformer is shown in figure 3-3. Because the input transformer is located in the power supply and is the ultimate source of power for both the load and the power supply, it is called the power transformer. The transformer has the ability to deliver both 6.3- and 5-volt ac filament voltages to the electron tubes. The high-voltage winding is a 1:3 step-up winding and delivers 360 volts ac to the rectifier. This transformer also has what is called a center tap. This center tap provides the capability of developing two high-voltage outputs from one transformer.

Rectifiers

Since a diode vacuum tube will pass current in only one direction, it is ideally suited for converting alternating current to direct current. If an ac voltage is applied to a diode, the diode will conduct only during the positive alternating of voltage when the plate of the diode is made positive with respect to the cathode.

Figure 3-4 shows a diode connected across the 120-volt ac line. During the positive alternation of the source voltage, the sine wave applied to the tube makes the plate positive with respect to the cathode. At this time, the diode conducts and plate current flows from the negative supply lead, through the milliammeter, through the tube, to the positive supply lead. This is indicated by the shaded area of the output waveform. This current exists during the entire period of time that the plate is positive with respect to the cathode (for the first 180 degrees of the input sine wave).

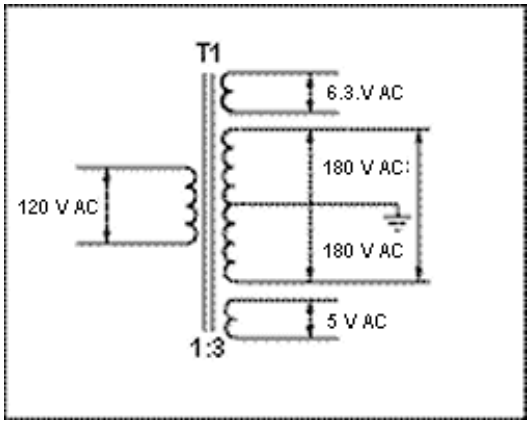

Figure 3-3. Typical Power Transformer.

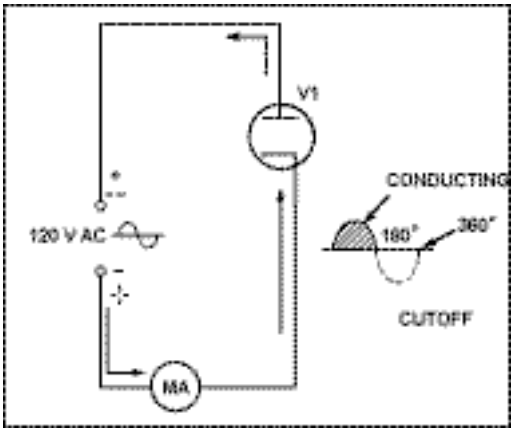

Figure 3-4. Simple Diode Rectifier.

During the negative alternation of plate voltage (dotted polarity signs), the plate is driven negative and the tube cannot conduct. When conditions are such that the tube cannot conduct, the tube is said to be in cutoff. This is indicated by the dotted waveform. The tube will be in cutoff and on current will flow for the entire negative alternation.

For each 360-degree cycle of input voltage, the tube conducts for 180 degrees and is in cutoff for 180 degrees. The circuit current therefore has the appearance of a series of positive pulses, as shown by the shaded areas. Although the current is in the form of pulses, the current always flows through the circuit in the same direction. Current that flows in pulses in the same direction is called pulsating dc. The diode has thus rectified the input voltage. Although the principle of rectification applies to all rectifier circuits, some rectifiers are more efficient than others. The three rectifier circuits most commonly used in electronics today are the half-wave, full-wave, and bridge.

Half-wave Rectifier Circuit. Figure 3-5 is a diagram of a complete half wave rectifier circuit. For the diode to be used as a rectifier, it must be connected in series with a load device (R_L for this circuit) through which the direct current flows.

Because electronic equipment requires various input voltages, it is necessary to have a rectified voltage that is greater (or smaller in some cases) than the source voltage. The rectifier plate circuit is supplied power from a step-up (or step-down) transformer. Note that the transformer has the two secondary windings. The lower winding supplies high voltage to the plate and cathode of the diode, and the upper winding supplies a low ac voltage to the filaments of the diode. Also, the cathode of the diode is connected to the secondary winding of the transformer through the load resistor (RL). Any current flowing through the tube also flows through the load resistor causing a voltage to be developed across it. The magnitude of the voltage developed across the load resistor is directly proportional to the amount of current flowing through it (Ohm's law: E = IR).

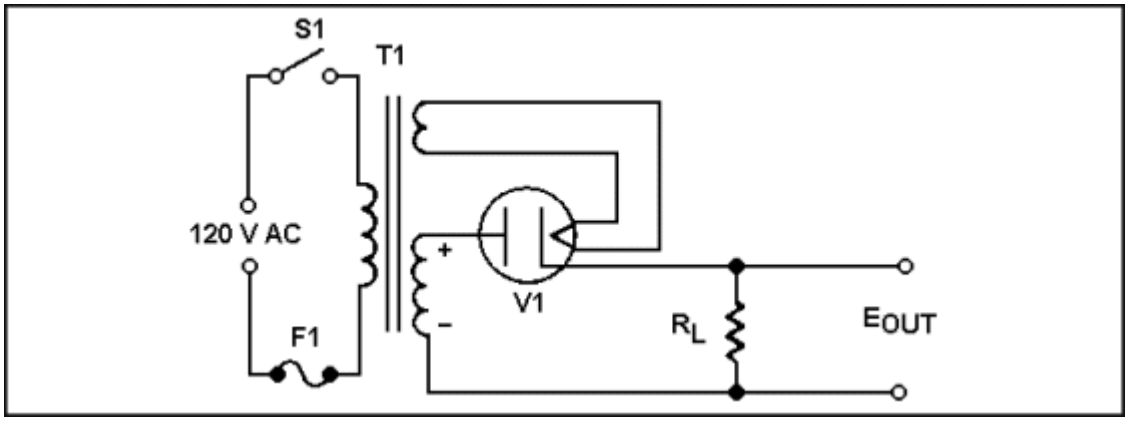

Figure 3-5. Half-wave Rectifier Circuit.

In figure 3-6 the diode (V1) and load resistor (R_L) are in series with the secondary winding of the transformer. During the positive alternation of the input, as the voltage in the secondary winding increases, the current through the diode (V1) and load resistor (R_L) increases. Since the diode tube and the load resistor form a series circuit, the same current flows through both the tube and the resistor. This current produces a voltage drop across the tube and the load resistor, which have polarities as shown. Since the plate resistance of the tube is only about 500 ohms and the load resistor is 10,000 ohms, approximately 95 percent of the applied voltage of the 425 volts is dropped across the load-resistor (425 x .95 = 404 V) and 5 percent (425 x .05 = 21 V) across the tube.

During the negative half of the alternation of input voltage, the tube cannot conduct, and no current flows in the circuit. Since there is no current flow through R_L, the load voltage remains at zero volts throughout the negative alternation. During this time the entire negative alternation is felt across the tube. The reason for this is derived from Kirchhoff's law that states:

$$E_L + E_b = E_a$$

The sum of the load voltage and diode voltage equals the applied voltage.

Since a half-wave rectifier conducts once for each full cycle of input voltage, the frequency of the pulses is the same as the frequency of the input sine wave. The output pulse frequency is called ripple frequency. If the rectifier circuit is supplied power from a 60-hertz ac line voltage, 60 pulses of load current will occur each second. Therefore, the ripple frequency of a halfwave rectifier is the same as the line frequency.

If a series of current pulses like those obtained from a half-wave rectifier is applied to a load resistor, an average amount of power will be dissipated over a given period of time. This average dc power is determined by the amplitude of the pulses and the time delay between pulses. The higher the peak amplitude of the pulses or the less the time between pulses, the greater the average dc power supplied to the load. To determine average dc voltage (E_{avg}), it is necessary to know the average value of the pulses and the peak value of load voltage. This is illustrated in figure 3-7.

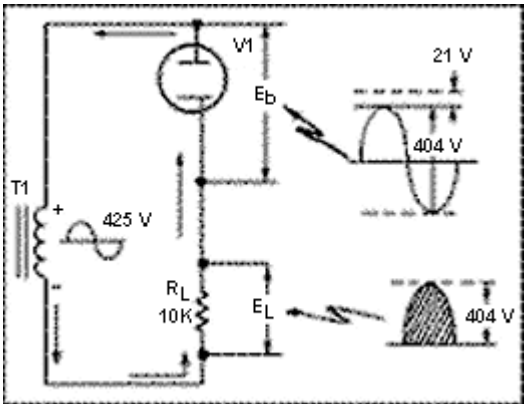

Figure 3-6. Simplified Half-wave Rectifier Circuit and Waveforms

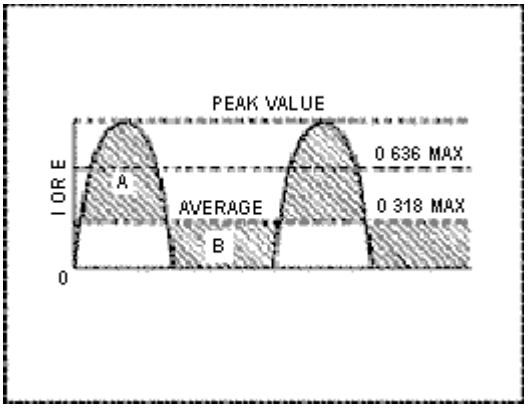

Figure 3-7. Peak and Average Values for a Half- wave Rectifier

Since current and voltage waveforms in a half-wave rectifier circuit are essentially half-sine waves, a conversion factor can be developed on this basis. The average value for a sine wave is 0.637 times its peak or maximum value. Therefore, to obtain the average value of a half-wave rectifier output, use half the value of 0.637 (.318) times the peak or maximum voltage as expressed in the following equation:

Where:

E_{max} = the peak value of the load voltage pulse
$E_{avg} = 0.318 \times E_{max}$ (the average load voltage)

In most applications the drop across the rectifier tube is small compared to the load voltage, and E_{max} in the above equation can be assumed to be the same as the peak value of the input sine wave. Since the load current has the same wave shape as the load voltage, the equation can be modified so as to apply to the load current.

Where:

I_{max} = the peak load current
$I_{avg} = 0.318 \times I_{max}$ (the average load current)

If a line is drawn through the rectified waveform at a point that is 0.318 of the distance from zero to maximum, the waveform will be divided so that area A is equal to area B. Therefore, current or voltage pulses with a value of 0.318 of the peak value have the same effect on the load as a steady voltage or current.

The half-wave rectifier uses the transformer during only one-half of the cycle. Therefore, for any given size transformer, less power is developed than if the transformer were used on both halves of the cycle. In other words, to obtain large amounts of power, the half-wave transformer must be relatively large in comparison to what it would have to be if both halves of the cycle were used. This disadvantage limits the use of the half-wave rectifier to applications that require a very small current drain. The half-wave rectifier is widely used for commercial ac and dc radio receivers and other applications where inexpensive voltage supplies suffice.

Full-wave Rectifier Circuit. Half-wave rectifiers place many limitations on electronic equipment. In the development of another type of rectifier circuit, one of the factors that had to be considered was how to use the full output from the transformer to obtain the highest average voltage and current. Thus the full-wave rectifier was developed. A full-wave rectifier is a device that has two or more diodes arranged so that the load current flows in the same direction during each half-cycle of the ac supply.

A schematic diagram of a simple full-wave rectifier is shown in figure 3-8. The transformer supplies the source voltage for two rectifier tubes (V1 and V2). This power transformer has a center-tapped high-voltage secondary winding that is divided into two equal parts (W1 and W2). W1 provides the source voltage for V1 and the other winding (W2) provides the source voltage for V2. The connections to the diodes are arranged so that the diodes conduct on alternate half-cycles.

During one alternation of the secondary voltage, the polarities will be as shown in figure 3-8. The source for diode V2 is the voltage induced into the lower half of the transformer secondary winding (W2). At the specific time shown in the figure, the plate voltage on V2 is negative, and V2 cannot conduct.

Throughout the period of time during which the plate of V2 is negative, the plate of V1 is positive. This is illustrated by the polarity signs across W1, which indicate the source for V1. Since the plate of V1 is positive, it conducts, causing current to flow through the load resistor in the direction shown by the arrow.

Figure 3-9 shows the next half-cycle of secondary voltage. The polarities across W1 and W2 are reversed. During this alternation the plate of V1 is driven negative, and V1 cannot conduct. For the period of time that V1 is negative, the plate of V2 is positive, permitting V2 to conduct. Note that the plate current of V2 passes through the load resistor in the same direction as did the plate current of V1. In this circuit arrangement, a pulse of load current flows during each alternation of the input cycle. Since both alternations of the input voltage cycle are used, the circuit is called a full-wave rectifier.

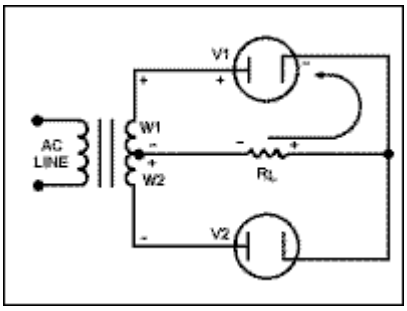

Figure 3-8. Simple Full-wave Rectifier (First Alternation).

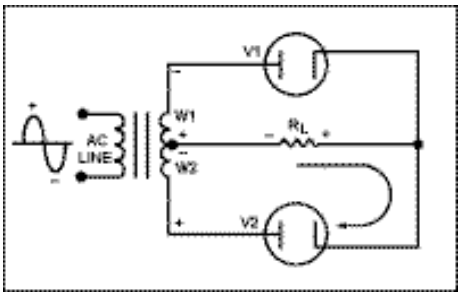

Figure 3-9. Simple Full-wave Rectifier (Second Alternation).

A practical full-wave rectifier circuit is shown in figure 3-10. It uses two diodes (V1 and V2) and a center-tapped transformer (T1). When the center tap is grounded, the voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other. Thus, when the voltage at point A is positive with respect to ground, the voltage at point B is negative with respect to ground. The operation of the circuit during one complete cycle follows.

During the first half-cycle (indicated by solid arrows) the plate of V1 is positive with respect to ground, and the plate of V2 is negative. As shown, current flows from ground (center tap), up through the load resistor (R_L), and through diode V1 to point A. In the transformer, current flows from point A, through the upper winding, and back to ground (center tap). When V1 conducts, it acts like a closed switch so that the positive half-cycle is felt across the load.

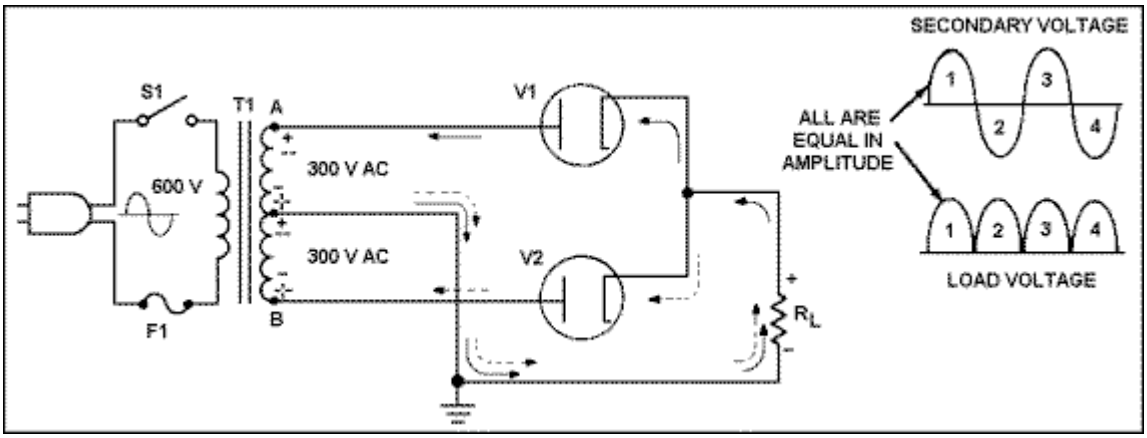

Figure 3-10. Complete Full-wave Rectifier.

During the second half-cycle (broken lines) the polarity of the applied voltage has reversed. Now the plate of V2 is positive with respect to ground, and the plate of V1 is negative. Now only V2 can conduct. Current now flows, as shown, from ground (center tap), up through the load resistor (R_L), and through diode V2 to point B of T1. In the transformer, current flows from point B, up through the lower windings, and back to ground (center tap). The current flows across the load resistor (R_L) in the same direction for both halves of the input cycles.

When the output waveform from the full-wave rectifier is examined, it consists of two pulses of current (or voltage) for each cycle of input voltage. The ripple frequency at the output of the full-wave rectifier is therefore twice the line frequency.

The higher ripple frequency at the output of a full-wave rectifier has a distinct advantage: because of the higher pulse frequency, the output is closely approximate to pure dc. This higher frequency also makes filtering easier than the output of the half-wave rectifier.

In terms of peak value, the average value of current and voltage at the output of the full-wave rectifier is twice as great as the average current or voltage at the output of the half-wave rectifier. The relationship between peak and average values is illustrated in figure 3-11. Since the output waveform is essentially a sine wave with both alternations at the same polarity, the average current or voltage is 63.7 percent (or .637) of the peak current or voltage.

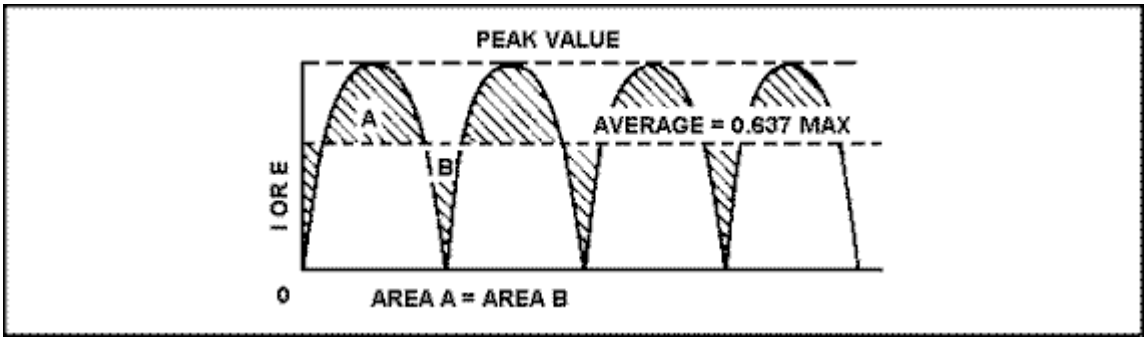

Figure 3-11. Peak and Average Values for a Full-wave Rectifier.

As an equation:

Where:

E_{max} = the peak value of the load voltage pulse
E_{avg} = 0.637 x Emax (the average load voltage)

And where:

I_{max} = the peak value of the load current pulse Iavg = 0.637 x Imax (the average load current)
Example: The total voltage across the high-voltage secondary of a transformer used to supply a full-wave rectifier is 600 volts.

Solution: Since the total secondary voltage is 600 volts, each diode is supplied one-half of this value, or 300 volts. As the secondary voltage is an rms value, the peak load voltage is:

E_{max} =1.414 x E_S

E_{max} =1.414 x 300

E_{max} = 424 volts

The average load voltage is:

Eavg =0.637 x E_{max}

E_{avg} =0.637 x 424

E_{avg} = 270 volts

There are advantages and disadvantages in every circuit. The full-wave rectifier is no exception. By doubling the output frequency, the average voltage doubles and the resulting signal is easier to filter because of the high-ripple frequency. The only disadvantage is that the peak voltage in a full-wave rectifier is only half the peak voltage in a half-wave rectifier. This is because the secondary of the power transformer in a full-wave rectifier is centertapped; therefore, only half the source voltage goes to each diode.

Bridge Rectifier Circuit. Fortunately, there is a rectifier that produces the same peak voltage as a half-wave rectifier and the same ripple frequency as a full-wave rectifier. This circuit is called the bridge rectifier (figure 3-12). The input to the circuit is applied to the diagonally opposite corners of the network, and the output is taken from the remaining two corners.

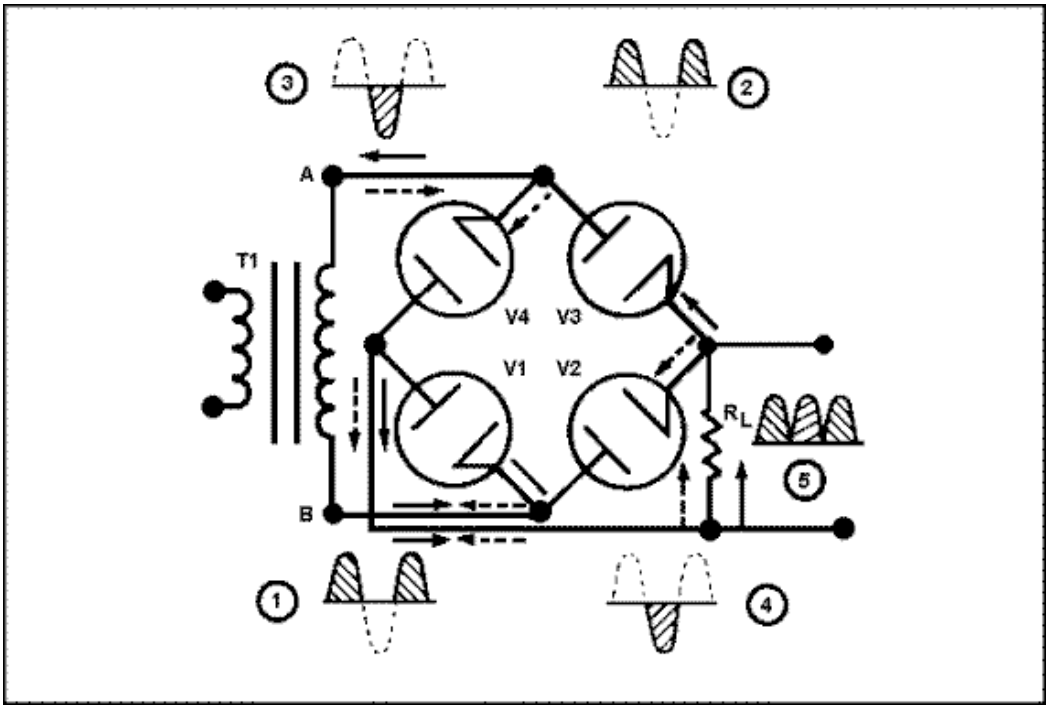

Figure 3-12. Bridge Rectifier Circuit.

During one half-cycle of the applied voltage, point A becomes positive with respect to point B by the amount of voltage induced into the secondary of the transformer. During this time, the voltage between points A and B may be considered to be impressed across V1, the load resistor RL, and V3, in series. The voltage applied across these tubes makes their plates more positive than their cathodes, and current flows from point B through V1 in an upward direction across the load resistor and through tube V3 to point A. This path is indicated by the solid arrows, and the waveform is shown as drawings 1 and 2. One half-cycle later the polarity across the secondary reverses, making the plates of V1 and V3 negative with respect to their cathodes. At the same time, the plates of V2 and V4 become positive with respect to their cathodes, and current flows in the direction indicated by the broken-line arrows. The current through RL is always in the same direction. This current, in flowing through RL, develops a voltage corresponding to that shown in waveform 5 of the figure. The bridge rectifier is a full-wave rectifier since current flows through the load during both half-cycles of the applied alternating voltage.

One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer the bridge rectifier produces a voltage output that is nearly twice that of the conventional full-wave circuit. This may be shown by assigning values to some of the components as shown in figure 3-13, views A and B. Assume that the same transformer is used in both circuits. The peak voltage developed between points X and Y is 1,000 volts in both circuits. In the conventional full-wave circuit, view A, the peak voltage from the center tap to either X or Y is 500 volts. Since only one diode can conduct at any instant, the maximum voltage that can be rectified at any instant is 500 volts. Therefore, the maximum voltage that appears across the load resistor is nearly, but never exceeds, 500 volts (because of the small voltage drop across the tube). In the bridge rectifier of view B, the maximum voltage that can be rectified is the full secondary voltage, which is 1,000 volts. Therefore, the peak output voltage across the load resistor is nearly 1,000 volts.

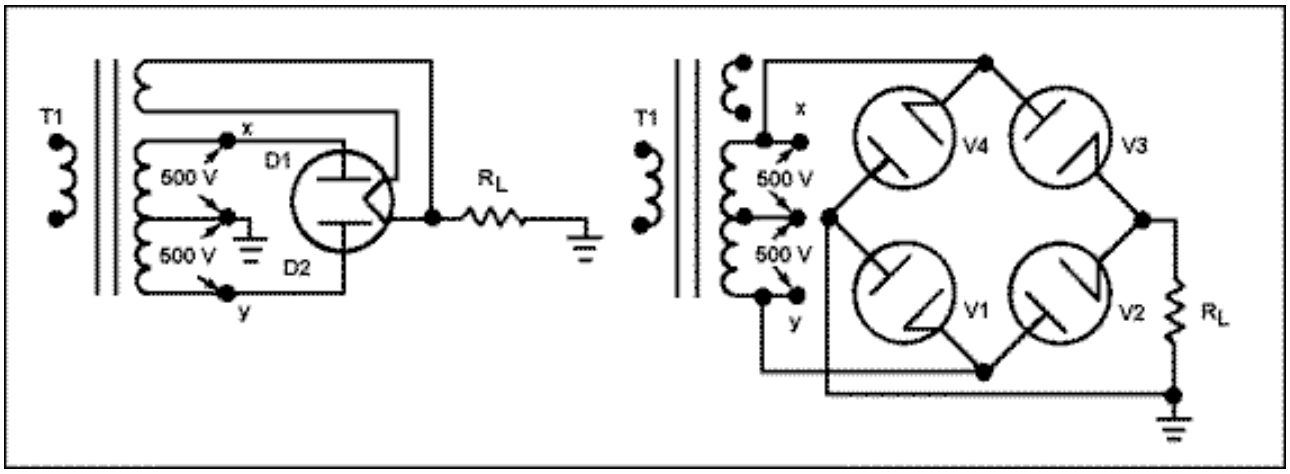

Figure 3-13. Comparison of Conventional Full-wave and Bridge Rectifiers.

Thus, with both circuits using the same transformer, the full-wave bridge circuit produces a higher output voltage than the conventional full-wave rectifier.

A second advantage of the bridge rectifier is the low ratio of peak inverse voltage to average output voltage. For this reason bridge rectifiers that use vacuum tubes are widely used in high-voltage power supply applications.

If directly heated diodes are used in a bridge rectifier, three separate filament transformers are required. This is due to the different potentials existing at the filaments of the diodes. The filaments of V2 and V3 in figure 3-14 are at the same potential, but the filament of V1 is at a different potential from either V2 or V4. The three filament transformers must be well insulated from each other, and from ground, because of the high potentials to which they are subjected. The use of indirectly heated diodes would solve the filament transformer problem, but the high potential difference between cathode and heater would be likely to result in arcing.

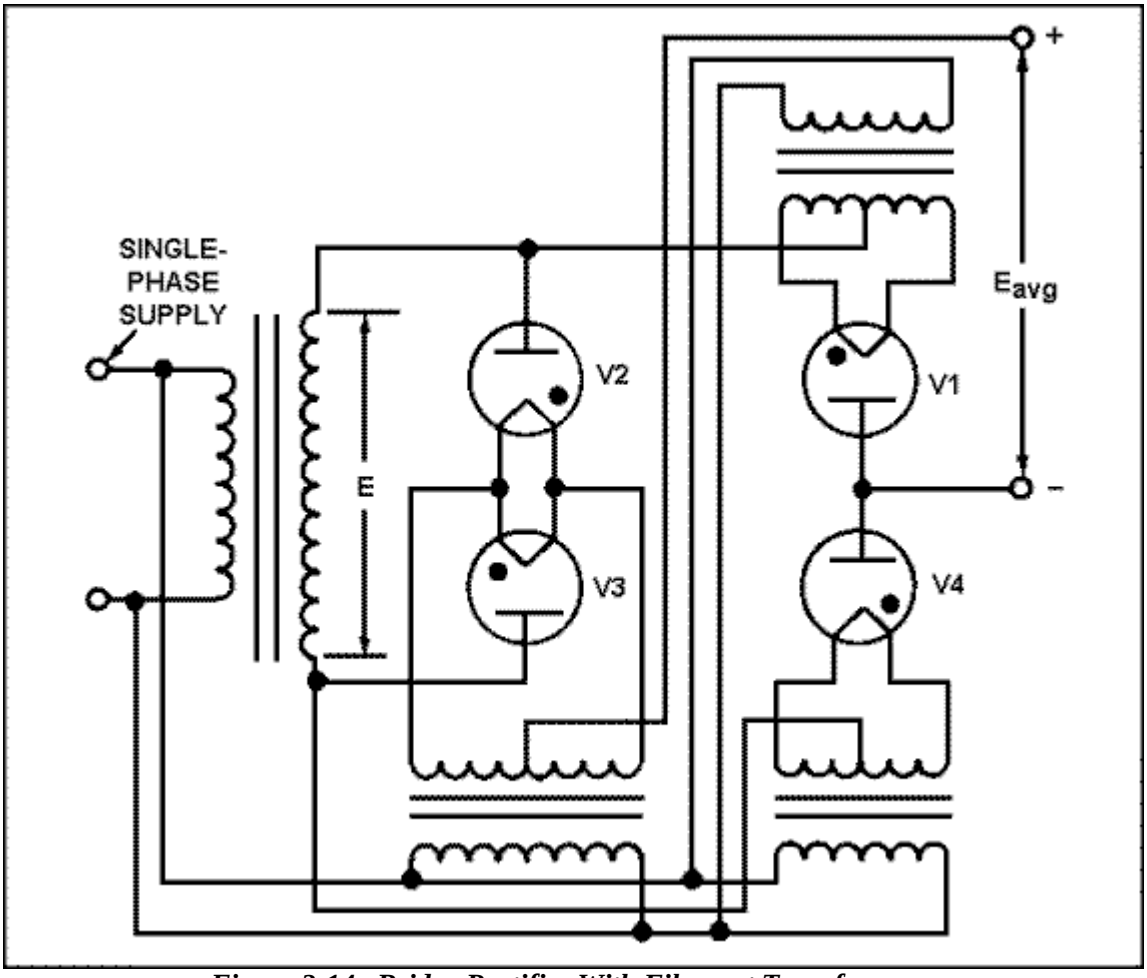

Figure 3-14. Bridge Rectifier With Filament Transformers.

Filters

While the output of a rectifier is a pulsating dc, most electronic circuits require a substantially pure dc for proper operation. This type of output may be provided by placing single or multisection filter circuits between the output of the rectifier and the load.

The four basic types of filter circuits are: sample capacitor filter, LC choke input filter, RC capacitor input filter (pi-type), and LC input filter (pi-type). Filtering is accomplished by using various combinations of capacitors, inductors, or resistors. Inductors are used as series impedances to oppose the change in flow of alternating (pulsating dc) current. Capacitors are used as shunt elements to bypass the alternating components of the signal around the load (to ground). Resistors are used in place of inductors in low-current applications.

A capacitor opposes any change in voltage. The opposition to a change in voltage is called capacitive reactance (X_C) and is measured in ohms. The capacitive reactance is determined by the frequency (f) of the applied voltage and capacitance (C) of the capacitor.

$$Xc = \frac{1}{2\pi fC} \text{ or } \frac{.159}{fC}$$

From the formula, you can see that if frequency or capacitance is increased, the X_C will decrease. Since filter capacitors are placed in parallel with the load, a low X_C will provide better filtering than a high X_C. This is done by providing a better shunting effect of the ac around the load, as shown in figure 3-15.

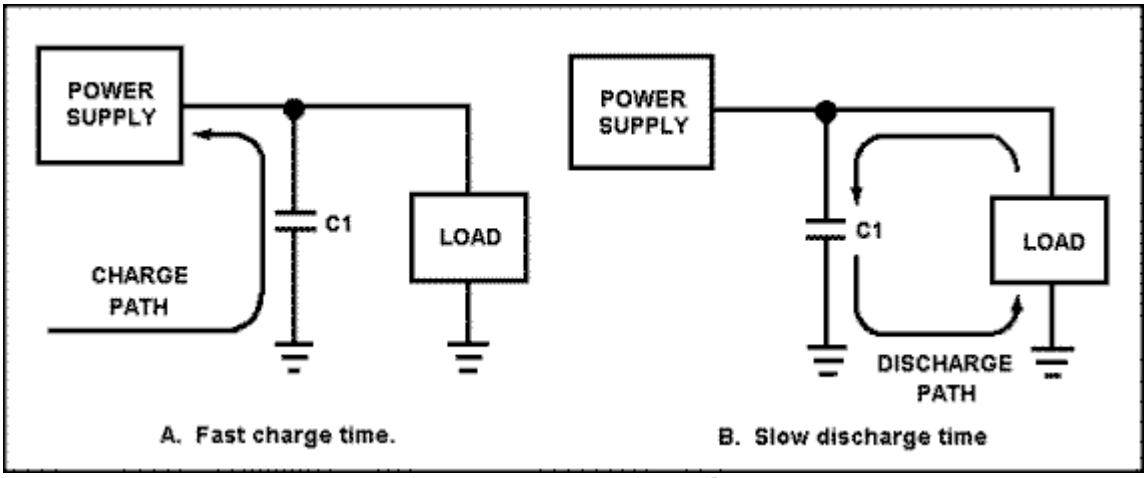

Figure 3-15. Capacitor Filter.

In order to obtain a steady dc input, the capacitor must charge almost instantaneously to the value of applied voltage. Once charged, the capacitor must retain the charge as long as possible. The capacitor must have a short charge time constant (view A) and a long discharge time constant (view B). This can be accomplished by keeping the internal resistance of the power supply as small as possible (fast charge time) and the resistance of the load as large as possible (slow discharge time).

One capacitor time constant is defined as the time it takes a capacitor to charge to 63.2 percent of the applied voltage or to discharge to 36.8 percent of its total charge. This can be expressed by the following equation:

$t = RC$

Where: R represents the resistance of the charge or discharge path

and: C represents the capacitance of the capacitor

A capacitor is considered fully charged after five RC time constants. To obtain a steady dc output voltage, the capacitor should charge rapidly and discharge as slowly as possible (see figure 3-16).

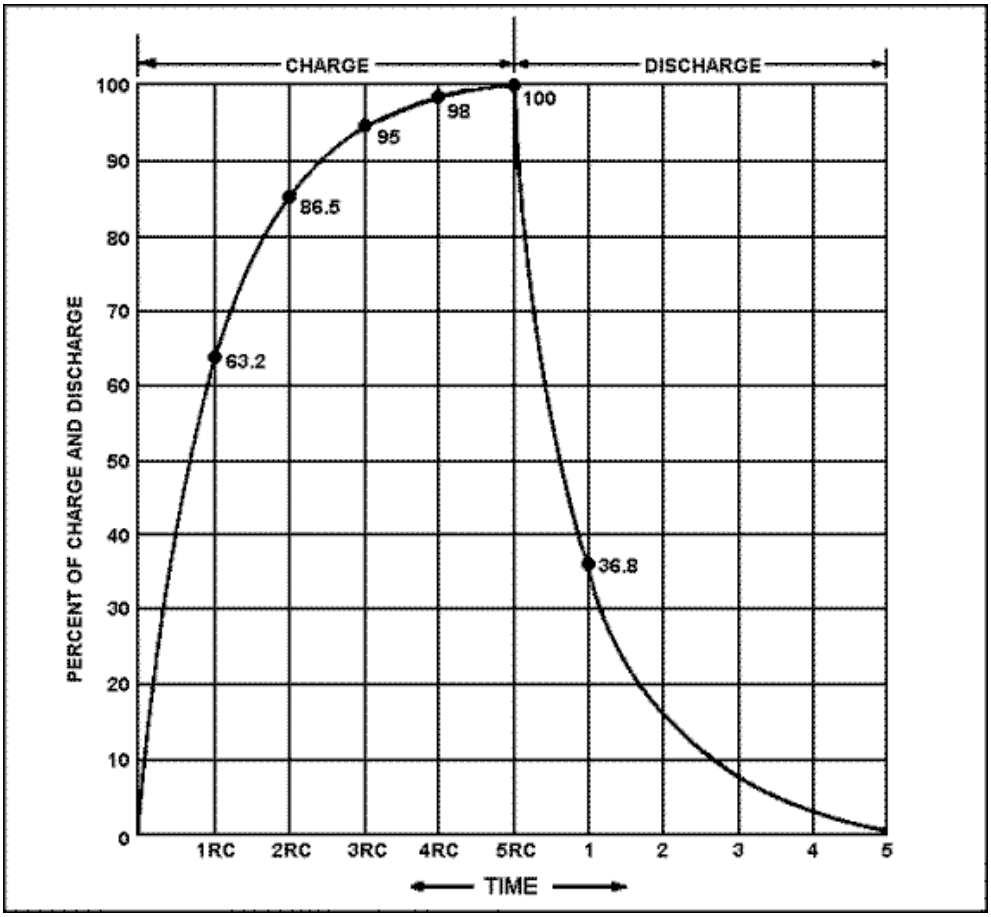

Figure 3-16. RC Time Constant Chart.

In filter circuits the capacitor is the common element to both the charge and discharge paths. Therefore, in order to obtain the longest possible discharge time, the capacitor has to be as long as possible. The capacitor acts as a short circuit around the load (as far as the ac component is concerned), and since

$$X_c = \frac{1}{2\pi fC}$$

the larger the value of the capacitor (C), the smaller the opposition (X_C) or resistance to ac.

An inductor opposes any change in current. A change in current through an inductor produces a changing electromagnetic field. The changing field, in turn, cuts the windings of the wire in the inductor and thereby produces a counterelectromotive force (cemf). It is the cemf that opposes the change in circuit current. Opposition to the change in current at a given frequency is called inductive reactance (X_L) and is measured in ohms. The inductive reactance (X_L) of an inductor is determined by the applied frequency and the inductance of the inductor. Mathematically the formula is: $X_L = 2\pi fL$.

This formula shows that if frequency or inductance is increased, the XL will increase. Since inductors are placed in series with the load (figure 3-17), the larger the XL, the larger the ac voltage developed across the inductor and the smaller the ac voltage developed across the load.

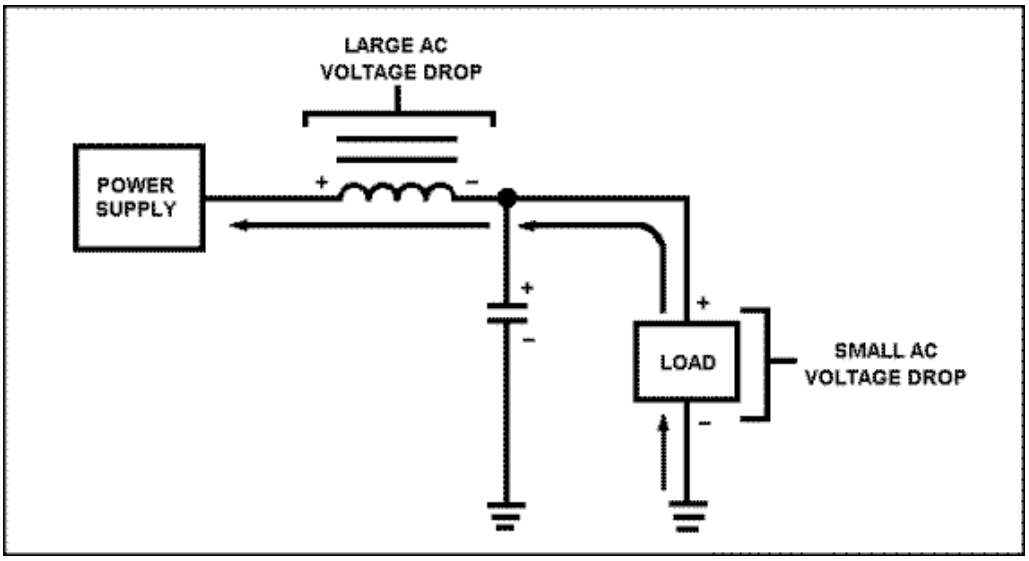

Figure 3-17. Voltage Drop in an Inductive Filter.

As illustrated in figure 3-18, when the current starts to flow through the coil, an expanding magnetic field builds up around the inductor. This magnetic field around the coil develops the cemf that opposes the change in current. When the rectifier current decreases as shown in figure 3-19, the magnetic field collapses and again cuts the turns (windings) or wire, thus inducing current into the coil. This additional current adds to the rectifier current and attempts to keep it at its original level.

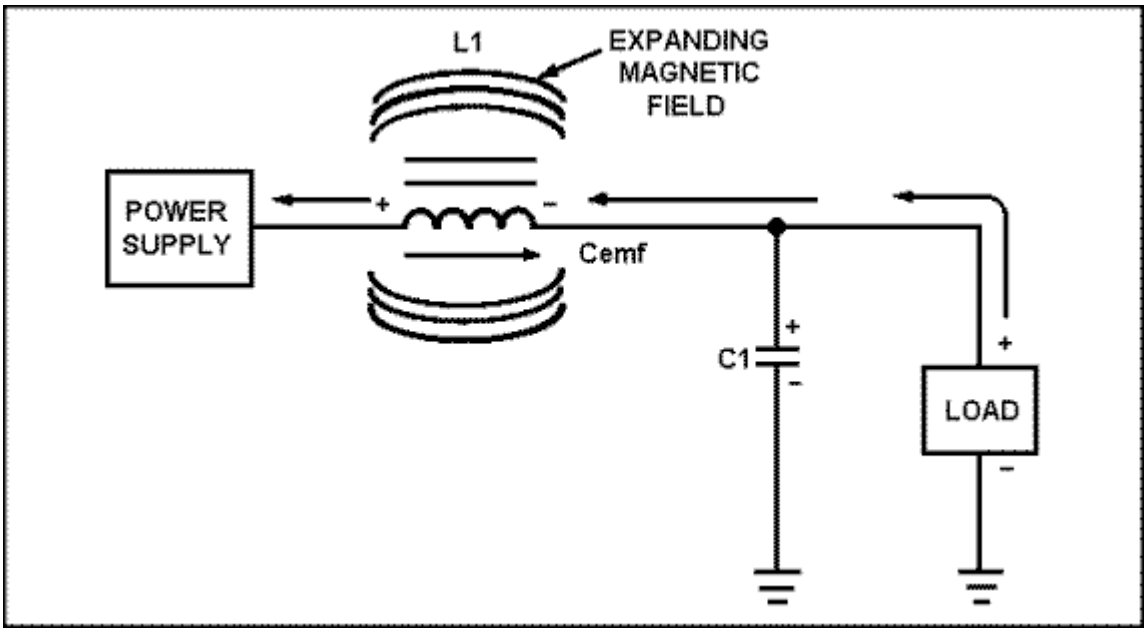

Figure 3-18. Inductive Filter (Expanding Field).

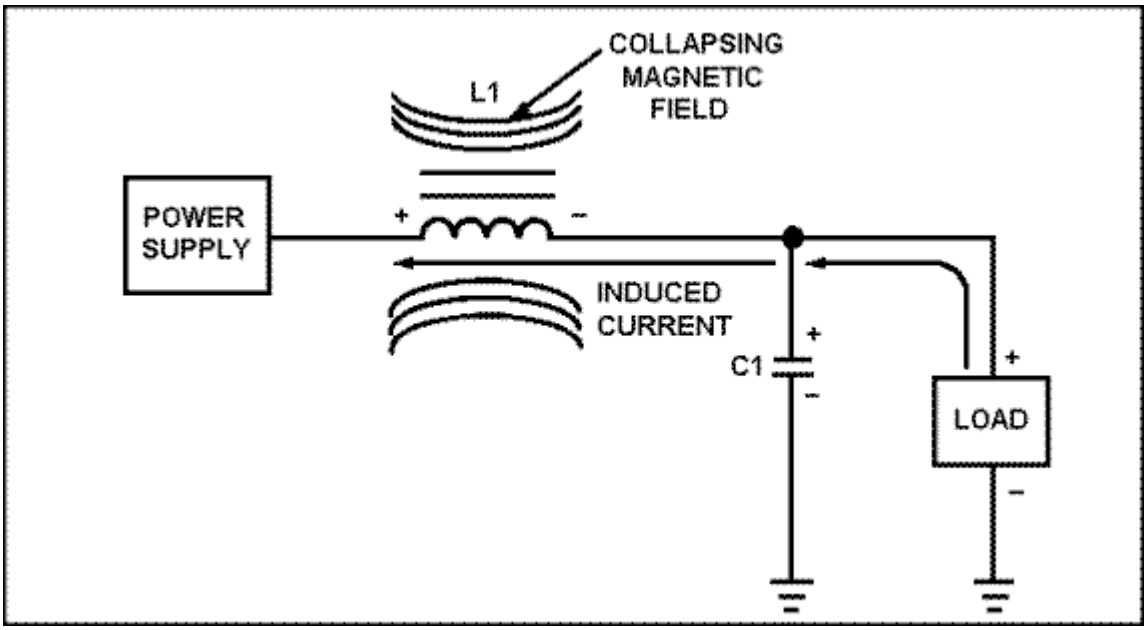

Figure 3-19. Inductive Filter (Collapsing Field).

Capacitor Filter. The capacitor filter is the most basic type of power supply filter. The application of this filter is very limited. It is sometimes used on extremely high-voltage, low-current power supplies for cathode ray and similar electron tubes that require very little load current from the supply. This filter is also used in application where the power supply ripple frequency is not critical and can be relatively high. The filter shown in figure 3-20 consists of a single-filter element. This capacitor (C1) is connected across the output of the rectifier in parallel with the load. The RC charge time of the filter capacitor (C1) must be short and the RC discharge time must be long to eliminate ripple action when using this filter. In other words, the capacitor must charge up fast with preferably no discharge at all. Better filtering also results when the frequency is high; therefore, the full-wave rectifier output is easier to filter than the half-wave rectifier because of its higher frequency.

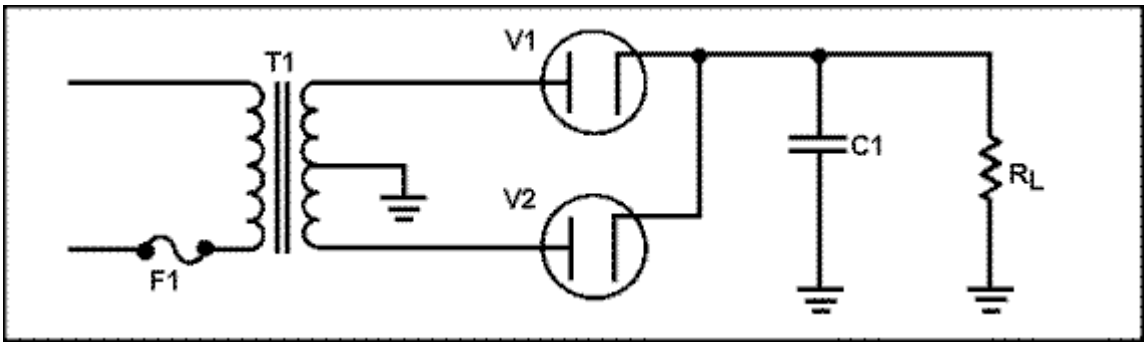

Figure 3-20. Full-wave Rlectifier With a Capacitor Filter.

For a better understanding of the effects that filtering has on Eavg, a comparison can be drawn between the rectifier circuits without filters in figure 3-21 to those with filters in figure 3-22. The output waveforms in figure 3-21 represent the unfiltered outputs of the half-wave and full-wave rectifier circuits. Current pulses flow through the load resistance (R_L) each time a diode

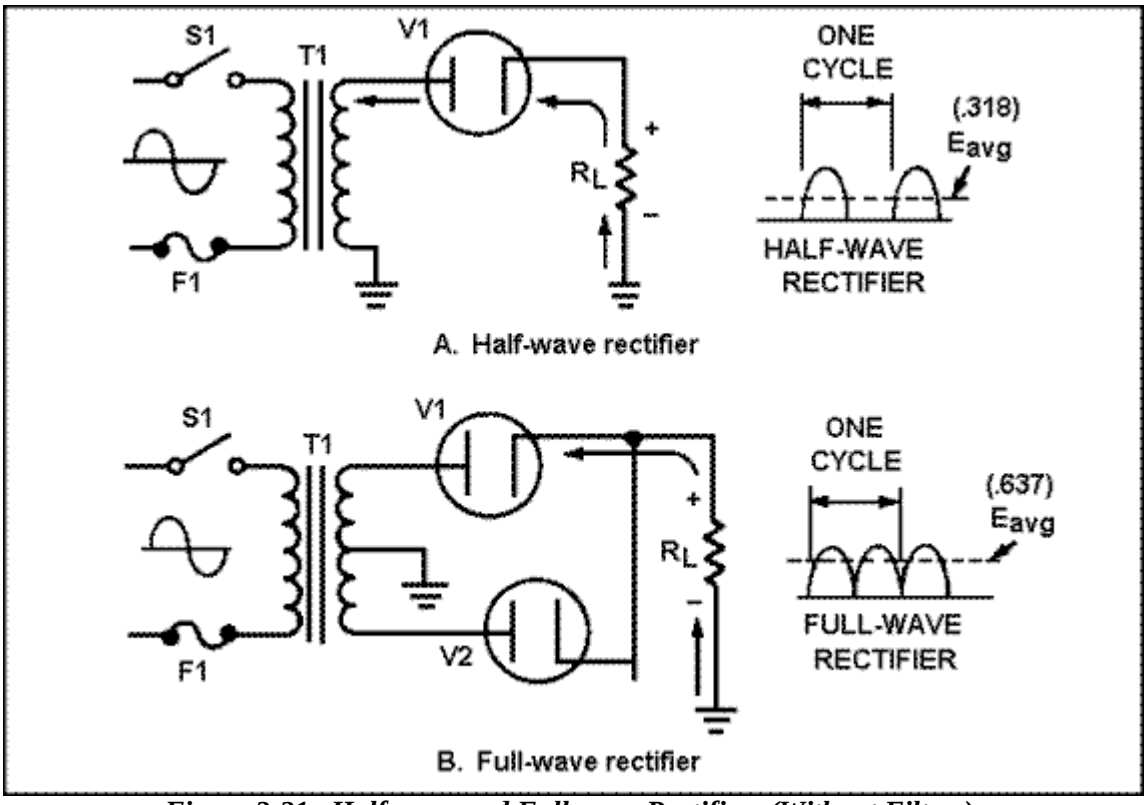

Figure 3-21. Half-wave and Full-wave Rectifiers (Without Filters).

conducts. The broken line indicates the average value of output voltage. For the half-wave rectifier, Eavg is less than half the peak output voltage (or approximately 0.637). This value is still less than the applied voltage. With no capacitor connected across the output of the rectifier circuit, the waveform has a large pulsating component (ripple) compared with the average or dc component. Refer to figure 3-22. When a capacitor is connected across the output (in parallel with R_L), the average value of output voltage (E_{avg}) is increased due to the filtering action of capacitor C1.

The value of the capacitor is fairly large (several microfarads); it thus presents a relatively low reactance to the pulsating current and stores a substantial charge. The rate of charge for the capacitor is limited only by the resistance of the conducting diode, which is relatively low. The RC charge time of the circuit is, therefore, relatively short. As a result, when the pulsating voltage is first applied to the circuit, the capacitor charges rapidly and almost reaches the peak value of the rectifier voltage within the first few cycles. The capacitor attempts to charge to the peak value of the rectifier voltage anytime a diode is conducting, and tends to retain its charge when the rectifier output falls to zero. (The capacitor cannot discharge immediately.) The capacitor slowly discharges through the load resistance (R_L) during the time the rectifier is nonconducting.

The rate of discharge of the capacitor is determined by the value of capacitance and the value of the load resistance. If the capacitance and load resistance values are large, the RC discharge time for the circuit is relatively long. The addition of C1 to the circuit results in an increase in the average value of an output voltage (E_{avg}) and a reduction in the amplitude of the ripple component (E_r) present across the load resistance (see figure 3-22).

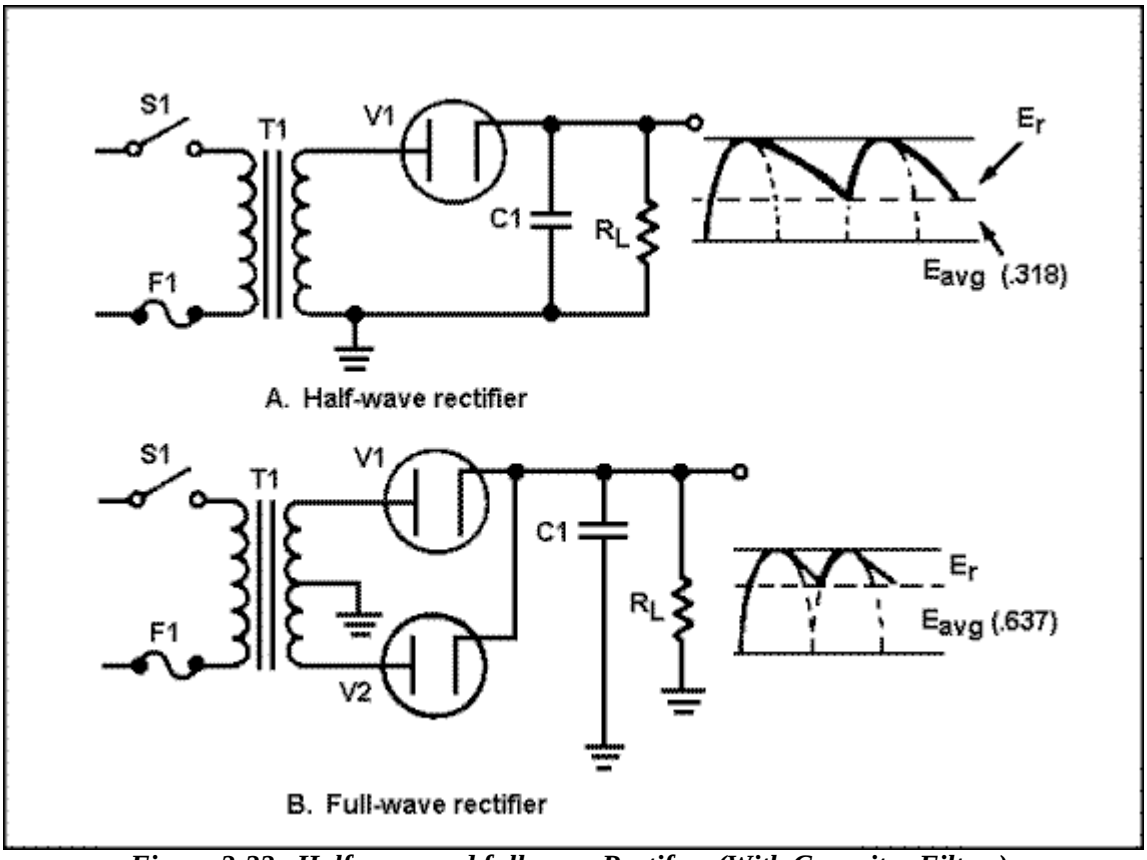

Figure 3-22. Half-wave and full-wave Rectifers (With Capacitor Filters).

The following is a complete cycle of operation using a half-wave rectifier, a capacitive filter (C1), and a load resistor (RL). As shown in figure 3-23, C1 is assumed to be large enough to ensure a small reactance to the pulsating rectified current. The resistance of RL is assumed to be greater than the reactance of C1 at the input frequency. When the circuit is energized, the diode conducts on the positive half-cycle and current flows through the circuit allowing C1 to charge. C1 will charge to approximately the peak value of the input voltage. The charge is less than the peak value because of the voltage drop across diode V1. The charge on C1 is indicated by the heavy, solid line on the waveform. As illustrated in figure 3-24, the diode (V1) cannot conduct on the negative half-cycle. The reason for this is that the plate of V1 is negative in respect to the cathode. During this interval, C1 discharges through load resistance R_L. The discharge of C1 produces the downward slope indicated by the solid line on the waveform in the figure.

During the discharge period, in contrast to the abrupt fall of the applied ac voltage from peak value to zero, the voltage across C1 (and across R_L) gradually decreases until the time of the next half-cycle of rectifier operation. For good filtering, the filter capacitor should charge as fast as possible and discharge as little as possible.

Since practical values of C1 and R_L ensure a more or less gradual decrease of the discharge voltage, a substantial charge remains on the capacitor at the time of the nest half-cycle of operation. As a result, no current can flow through the diode until the rising ac input voltage at the plate of the diode exceeds the voltage of the charge remaining on C1. The charge on C1 is the cathode potential of the diode. When the potential on the plate exceeds the

potential on the cathode (the charge on C1), the diode again conducts, and C1 commences to charge to approximately the peak value of the applied voltage.

After the capacitor has charged to its peak value, it begins to discharge. Since the fall of the ac input voltage on the plate is considerably more rapid than the decrease on the capacitor voltage, the cathode quickly becomes more positive than the plate, and the diode ceases to conduct.

Operation of the simple capacitor filter using a full-wave rectifier is basically the same as discussed for the half-wave rectifier. Refer to figure 3-25. Because one of the diodes is always conducting on either alternation, the filter capacitor charges and discharges during each half-cycle. (Note that each diode conducts only for that portion of time when the peak secondary voltage is greater than the charge across the capacitor.)

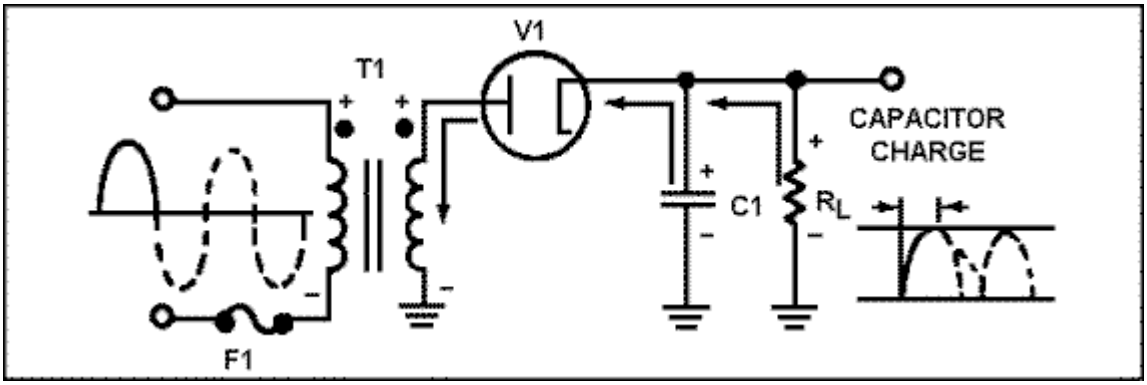

Figure 3-23. Half-wave Rectifier Capacitor Filter (Positive Input Cycle).

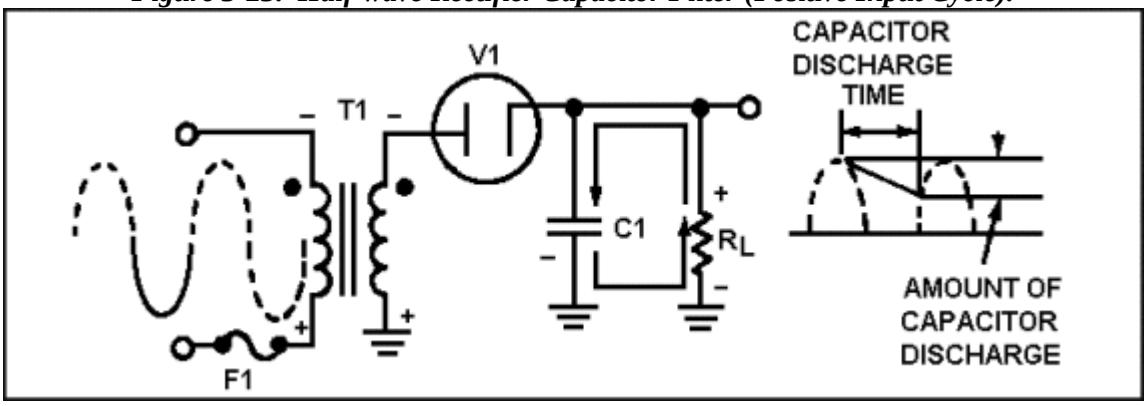

Figure 3-24. Half-wave Rectifier Capacitor Filter (Negative Input Cycle).

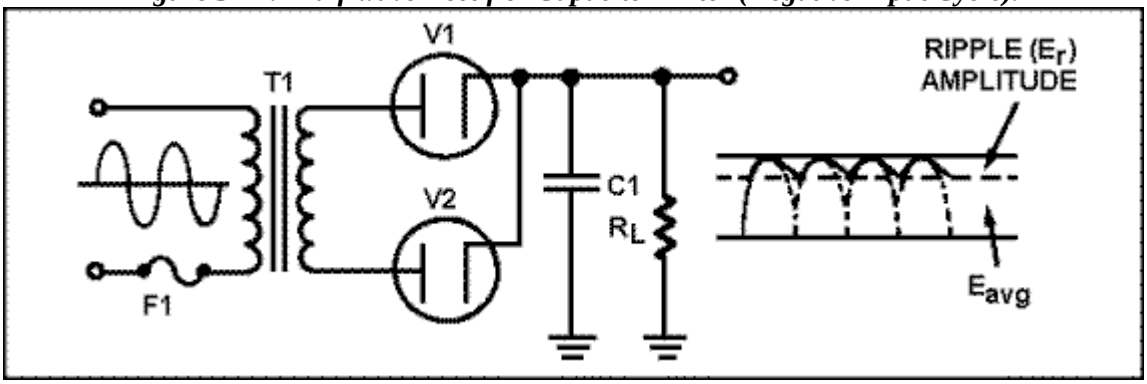

Figure 3-25. Full-wave Rectifier (With Capacitor Filter).

A major advantage of full-wave and bridge rectifiers over half-wave rectifiers is the ease of filtering their output voltages. The reason for this is that the ripple frequency is doubled: therefore, the time period the capacitor is allowed to discharge is cut in half. This means that the capacitor discharges less. Thus, ripple amplitude is less, and a smoother output voltage occurs.

The ripple component (E_r) of the output voltage is an ac voltage, and the average output voltage (E_{avg}) is the dc component of the output. Since the filter capacitor offers a relatively low impedance to ac, the majority of the ac component flows through the filter capacitor. The ac component is therefore bypassed (shunted) around the load resistance and the entire dc component (or E_{avg}) flows through the load resistance. To clarify this statement, refer to the formula for X_C in a half-wave and full-wave rectifier. First, you must establish some values for the circuit (see the following chart).

Half-wave Rectifier	*Full-wave Rectifier*
Frequency at rectificer output: 60 Hz	**Frequency at rectifier output: 120 Hz**
Value of filter capacitor: 30 μF	**Value of filter capacitor: 30 μF**
Load resistance (R_L): 10k Ω	**Load resistance (R_L): 10k Ω**
$X_C = \frac{1}{2\pi fC}$	$X_C = \frac{1}{2\pi fC}$
$X_C = \frac{.159}{fC}$	$X_C = \frac{.159}{fC}$
$X_C = \frac{.159}{60 \times .000030}$	$X_C = \frac{.159}{120 \times .000030}$
$X_C = \frac{.159}{.0018}$	$X_C = \frac{.159}{.036}$
$X_C = 88.3\ \Omega$	$X_C = 44.16\ \Omega$

The calculations show that by doubling the output frequency of the rectifier, the impedance of the capacitor is reduced by one-half. Therefore, by using the simple capacitor filter in conjunction with a full-wave or bridge rectifier, improved filtering is provided because the increased ripple frequency decreases the capacitive reactance of the filter capacitor. This allows the ac component to be passed through the capacitor more easily. Therefore, a full-wave rectifier output is easier to filter than that of a half-wave rectifier.

It should be obvious that the smaller the X_C of the filter capacitor in respect to the load resistance, the better the filtering action. By using the largest possible capacitor, the best filtering is achieved. The load resistance is also an important consideration. If load resistance is made small, the load current increases, and the average value of output voltage (E_{avg}) decreases. The RC discharge time constant is a direct function of the value of the load resistance; therefore, the rate of capacitor voltage discharge is a direct function of the current through the load. The greater the load current, the more rapid the discharge of the capacitor, and the lower the average value of output voltage. For this reason, the simple capacitor filter is seldom used with rectifier circuits that must supply a relatively large load current.

In general, with the supply voltage removed from the input to the filter circuit, one terminal of the filter capacitor can be disconnected from the circuit. Note that an undischarged capacitor retains its polarity and holds its charge for long periods of time. To be safe, use a proper safety shorting probe to discharge the capacitor to be tested with the power off before connecting test equipment or disconnecting the capacitor.

The capacitor can be checked by using a capacitance analyzer to determine its effective capacitance and leakage resistance. During these checks it is very important that correct polarity be observed if the capacitor is an electrolytic. A decrease in capacitance or losses within the capacitor can cause the output to be below normal and can cause excessive ripple amplitude.

If a suitable capacitance analyzer is not available, an indication of leakage resistance can be obtained by using an ohmmeter. Resistance measurements can be made across the terminals of the capacitor to determine whether it is shorted, leaky, or open. When testing electrolytic capacitors, set the ohmmeter to the high range and connect the test probes across the capacitor. Be careful to observe polarity. This is important because current flows through an electrolytic capacitor with less opposition in one direction than in the other. If the current polarity is not observed, an incorrect reading will result and damage can occur. When the test probes are first connected, a large deflection of the meter should take place, and then the pointer should return slowly toward the infinite-ohms position as the capacitor charges. For a good capacitor with a rated working voltage of 450 volts dc, the final reading on the ohmmeter should be over 500,000 ohms. (A rough rule of thumb for high voltage capacitors is at least 1,000 ohms per volt.) Low-voltage electrolytic capacitors (below 100 volts rating) should indicate approximately 100,000 ohms.

If no deflection is obtained on the ohmmeter when you are making the resistance check explained above, an open-circuit capacitor is indicated. A steady full-scale deflection of the pointer at zero ohms indicates that the capacitor being tested is shorted. An indication of a leaky capacitor is a steady reading on the scale somewhere between zero and the minimum acceptable value. (Be certain this reading is not caused by an in-circuit shunting part.) To be valid, these capacitor checks should be made with the capacitor completely disconnected from the circuit in which it operates.

In high-voltage filter capacitor applications, paper and oil-filled capacitors are used in addition to mica and ceramic capacitors (for low-capacitance values). In this case, polarity is of no importance unless the capacitor terminals are marked plus or minus. It is, however, good maintenance practice to use the output polarity of the circuit as a guide, connecting positive to positive, and negative to negative. Thus, any adverse effects of polarity on circuit tests are minimized and the possibility of damage to components or to test equipment is eliminated.

LC Choke Input Filter. The LC choke input filter is used primarily in power supplies where good voltage regulation is important and where the output current is relatively high and subject to varying load conditions. This filter is used in high-power applications such as those found in radar and communication transmitter power supplies.

This filter consists of an input inductor of filter choke (L1) and an output filter capacitor (C1) (see figure 3-26). Inductor L1 is placed at the input to the filter and is in series with the output of the rectifier circuit. Since the action of an inductor is to oppose any change in current flow, the inductor tends to keep a constant current flowing to the load throughout the complete cycle of the applied voltage. As a result, the output voltage never reaches the peak value of the applied voltage; instead, the output voltage approximates the average value of the rectified input to the filter, as shown in figure 3-27.

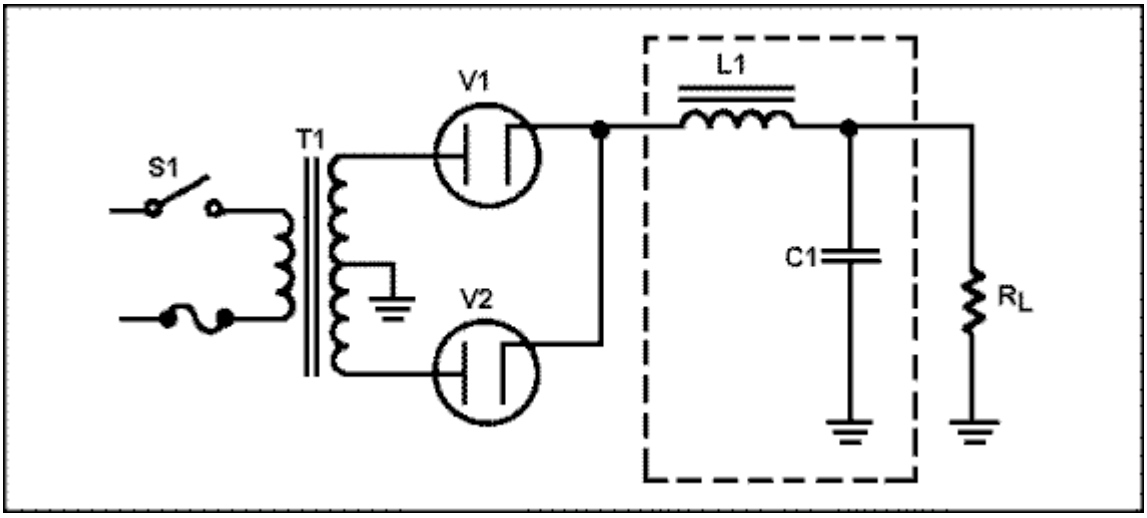

Figure 3-26. Full-wave Rectifier With LC Choke Input Filter.

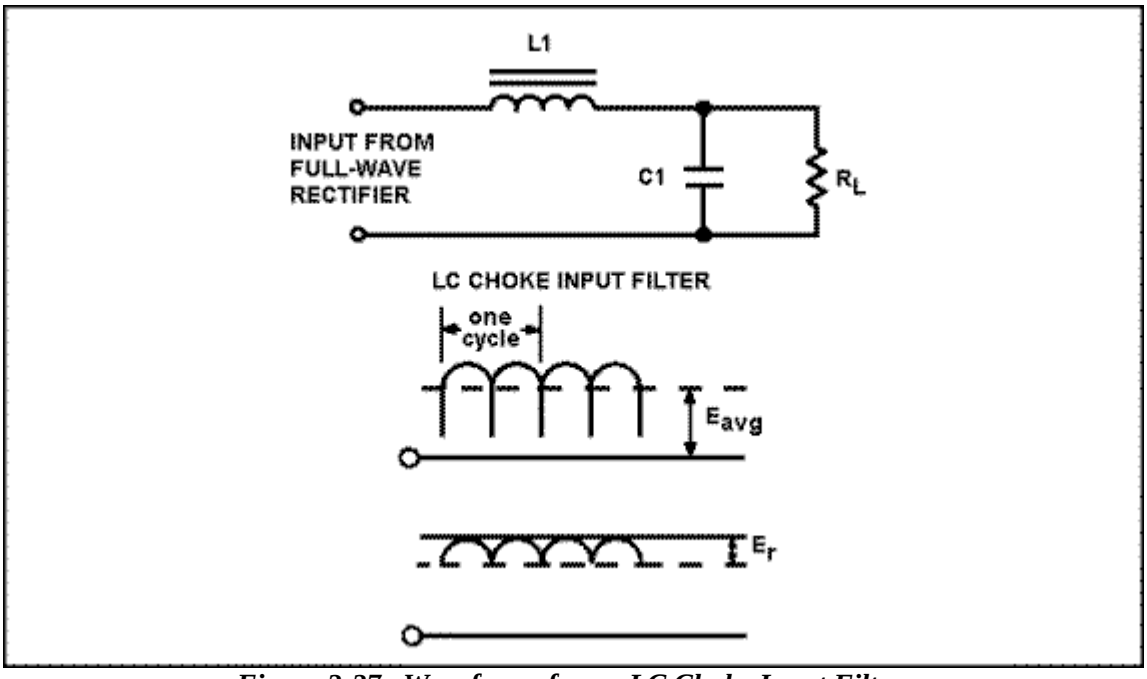

Figure 3-27. Waveforms for an LC Choke Input Filter.

The reactance of the inductor (X_L) reduces the amplitude of ripple voltage without reducing the dc output voltage by an appreciable amount. (The dc resistance of the inductor is just a few ohms.)

The shunt capacitor (C1) charges and discharges at the ripple frequency rate, but the amplitude of the ripple voltage (E_r) is relatively small because the inductor (L1) tends to keep a constant current flowing from the rectifier circuit to the load. In addition, the reactance of the shunt capacitor (X_C) presents a low impedance to the ripple component existing at the output of the filter, and thus shunts the ripple component around the load. The capacitor attempts to hold the output voltage relatively constant at the average value of the voltage.

The value of the filter capacitor (C1) must be relatively large in order to present a low opposition (X_C) to the pulsating current and to store a substantial charge. The rate of the charge of the capacitor is limited by the low impedance of the ac source (transformer), the small resistance of the diode, and the counter emf developed by the coil. Therefore, the RC charge time constant (figure 3-28) is short compared to its discharge time.

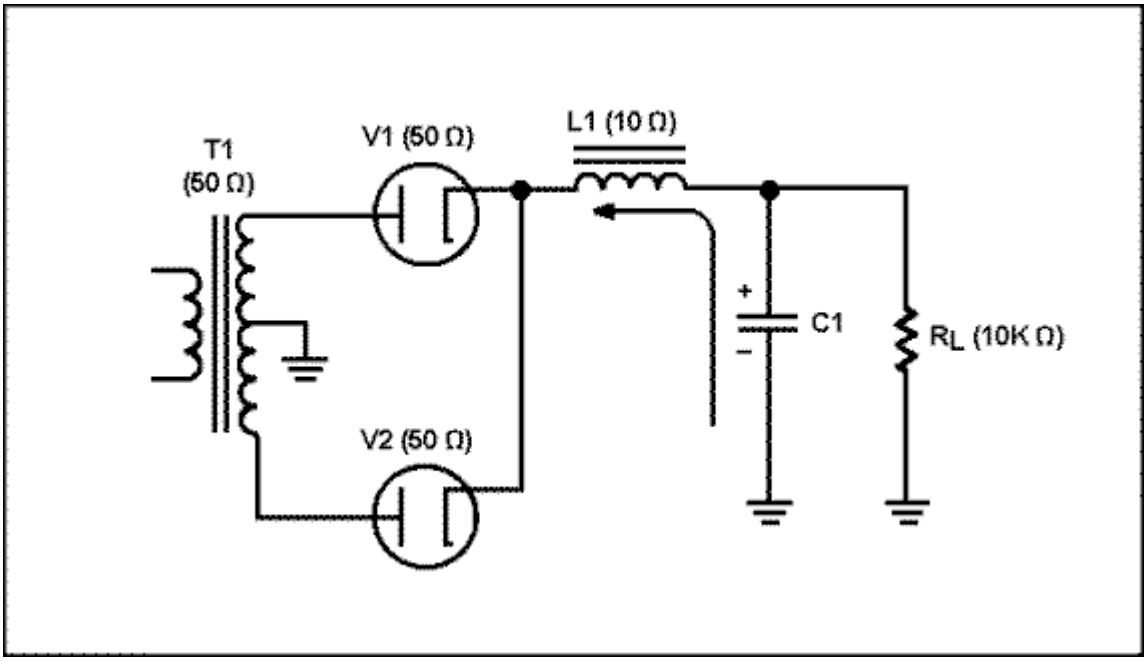

Figure 3-28. LC Choke Input Filter (Circuit Resistances).

As a result, when the pulsating voltage is first applied to the LC choke input filter, the inductor or filter choke (L1) produces a counter emf that opposes the constantly increasing input voltage. The net result is to prevent effectively the rapid charging of the filter capacitor (C1).

Thus, instead of reaching the peak value of the input voltage, C1 only charges to the average value of the input voltage. After the input voltage reaches its peak and decreases sufficiently, the capacitor (C1) attempts to discharge through the load resistance (R_L). C1 attempts to discharge as indicated in figure 3-29. Because of its relatively long discharge time constant, C1 can only partially discharge.

The larger the value of the filter capacitor, the better the filtering action. However, due to the physical size there is a practical limitation to the maximum value of the capacitor.

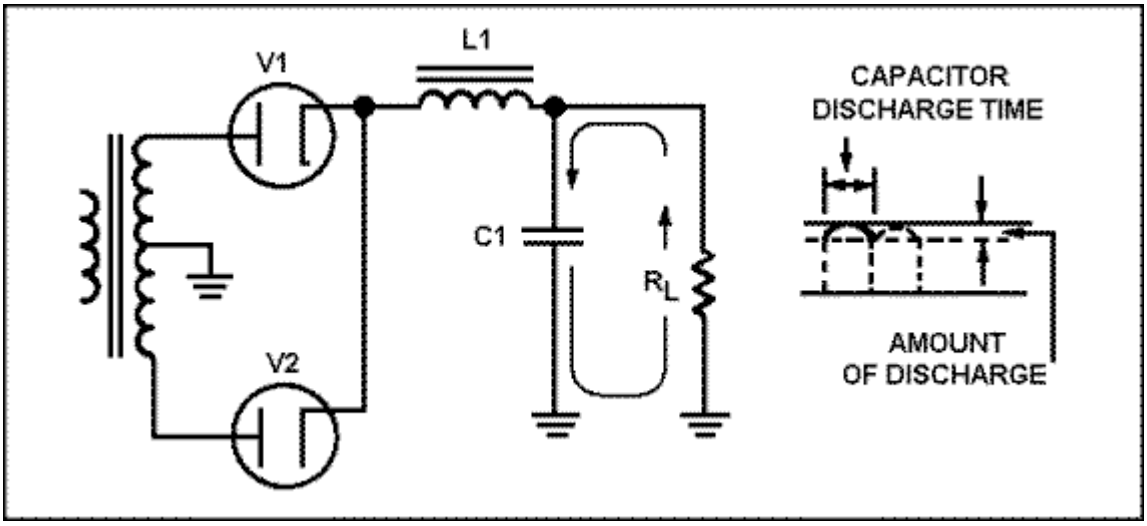

Figure 3-29. LC Choke Input Filter (Discharge Path).

The inductor or filter choke (L1) serves to maintain the current flow to the filter output (capacitor C1 and load resistance RL) at a nearly constant level during the charge and discharge periods of the filter capacitor.

The series inductor (L1) and the capacitor (C1) form a voltage divider for the ac component (ripple) of the applied input voltage. This is shown in figure 3-30. As far as the ripple component is concerned, the inductor offers a high impedance (Z), and the capacitor offers a low impedance. As a result, the ripple component (E_r) appearing across the load resistance is greatly attenuated (reduced). Since the inductance of the filter choke opposes changes in the value of the current flowing through it, the average value of the voltage produced across the capacitor contains a smaller value of ripple component (E_r) as compared with the value of ripple produced across the coil.

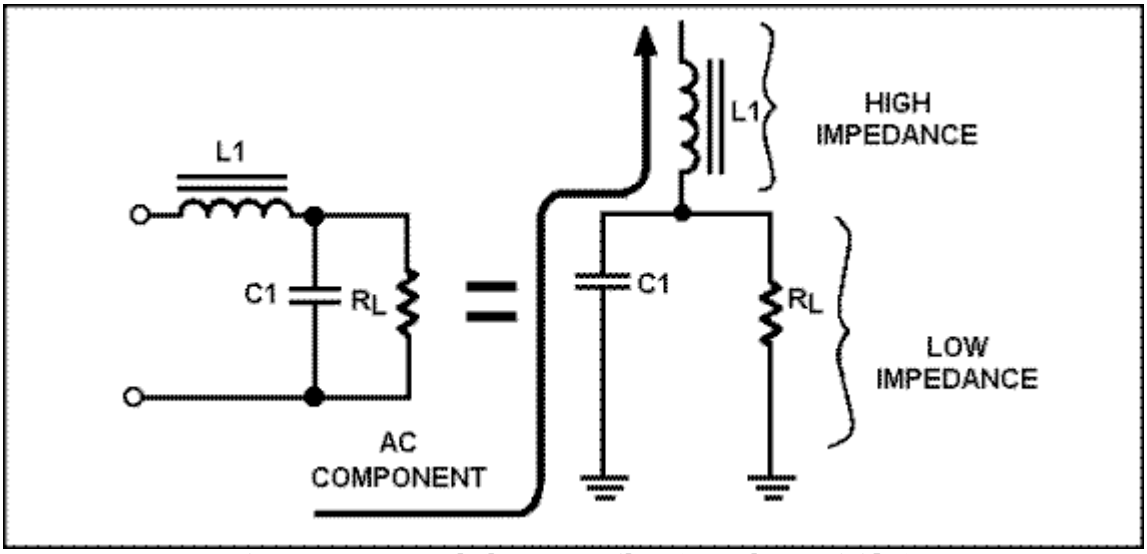

Figure 3-30. LC Choke Input Filter (as Voltage Divider).

Figure 3-31 illustrates a complete cycle of operation where a full-wave rectifier circuit is used to supply the input voltage to the filter. The rectifier voltage is developed across capacitor C1. The ripple voltage in the output of the filter is the alternating component of the input voltage reduced in amplitude by the filter section.

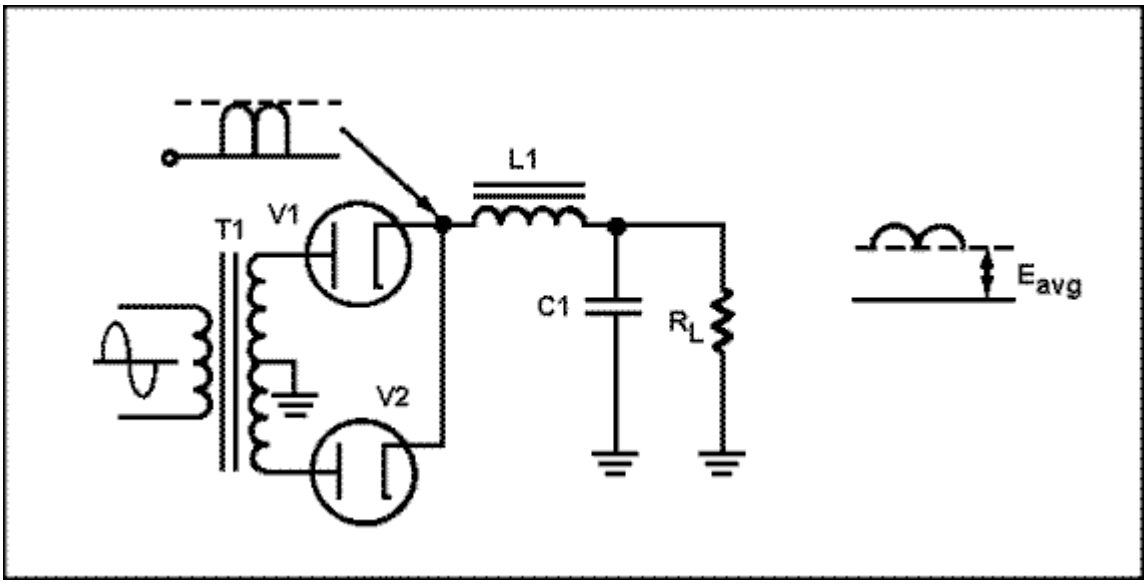

Figure 3-31. Filtering Action of an LC Choke Input Filter.

Each time the plate of a diode goes positive with respect to the cathode, the diode conducts and C1 charges. Conduction occurs twice during each cycle for a full-wave rectifier. For a 60-hertz supply, this produces a ripple frequency of 120 hertz. Although the diodes alternate (one conducts while the other is nonconducting), the filter input voltage is not steady. As the plate voltage of the conducting diode increases (on the positive half of the cycle), capacitor C1 charges, the charge being limited by the impedance of the secondary's transformer winding, the diode's forward (cathode-to-plate) resistance, and the counter emf developed by the choke. During the nonconducting interval (when the plate voltage drops below the capacitor charge voltage), C1 discharges through the load resistance R_L. The components in the discharge path have a long time constant; thus C1 discharges slower than it charges.

The choke (L1) is usually of a large value, on the order of 1 to 20 henries, and offers a large inductive reactance to the 120-hertz ripple component produced by the rectifier. Therefore, the effect that L1 has on the charging of the capacitor (C1) must be considered. Since L1 is connected in series with the parallel branch consisting of C1 and RL, a division of the ripple ac voltage and output dc voltage occurs. The greater the impedance of the choke, the less the ripple voltage that appears across C1 and the output. The dc output voltage is fixed mainly by the dc resistance of the choke.

The following is an example of the LC choke input filter using actual component values. For simplicity, the input frequency at the primary of the transformer will be 117 volts, 60 hertz. Both half-wave and full-wave rectifier circuits will be used to provide the input to the filter.

Starting with the half-wave configuration as shown in figure 3-32, the basic parameters are: with 117 volts ac rms applied to the T1 primary, 165 volts ac peak-to-peak is available at the secondary (117 V x 1.414 = 165 V). The ripple frequency of this half-wave rectifier is 60 hertz. Therefore, the capacitive reactance of C1 is:

$$X_c = \frac{1}{2\pi fC}$$

$$X_c = \frac{1}{(2)(3.14)(60)(10)(10^{-6})}$$

$$X_c = \frac{(1)(10^6)}{3768}$$

$$X_c = 265$$

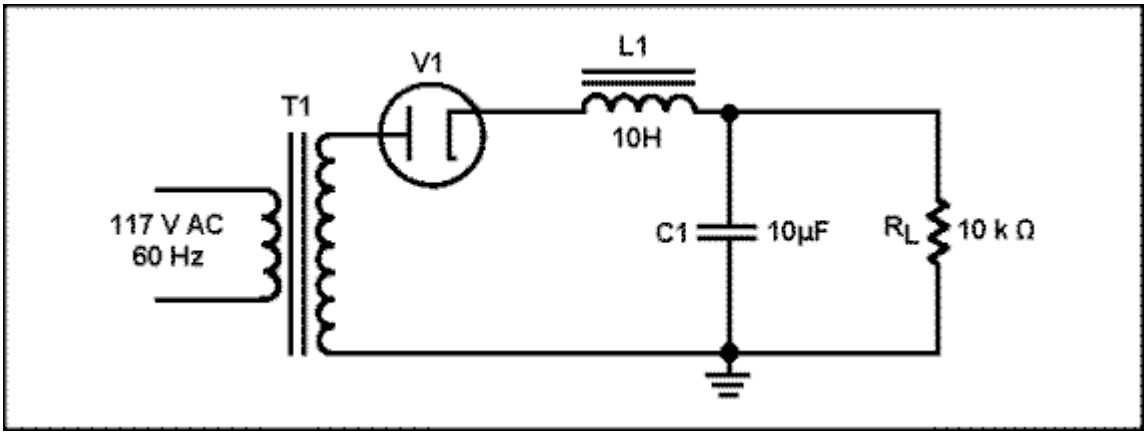

Figure 3-32. Half-wave Rectifier With an LC Choke Input Filter.

This means that the capacitor (C1) offers 265 ohms of opposition to the ripple current. Note, however, that the capacitor offers an infinite impedance to direct current. The inductive reactance of L1 is:

XL = 2 fL

XL = (2)(3.14)(60)(10)

XL = 3.8 kilohms

This shows that L1 offers a relatively high opposition (3.8 kilohms) to the ripple in comparison to the opposition offered by C1 (265 ohms). Thus, more ripple voltage will be dropped across L1 than across C1. In addition, the impedance of C1 (266 ohms) is relatively low in respect to the resistance of the load (10 kilohms). Therefore, more ripple current flows through C1 than the load. In other words, C1 shunts most of the ac component around the load.

Refer to figure 3-33. The 165 volts peak-to-peak 60 hertz provided by the rectifier consist of both an ac and a dc component. The first discussion will be about the ac component. Figure 3-33 shows that the capacitor (C1) offers the least opposition (265 ohms) to the ac component; therefore, the greatest amount of ac will flow through C1. (The heavy line indicates current flow through the capacitor.) Thus the capacitor bypasses, or shunts, most of the ac around the load.

By combining the X_C of C1 and the resistance of R_L into an equivalent circuit, you have a total resistance of 258 ohms.

$$RT = \frac{(R1)\quad(R2)}{R1 + R2}$$

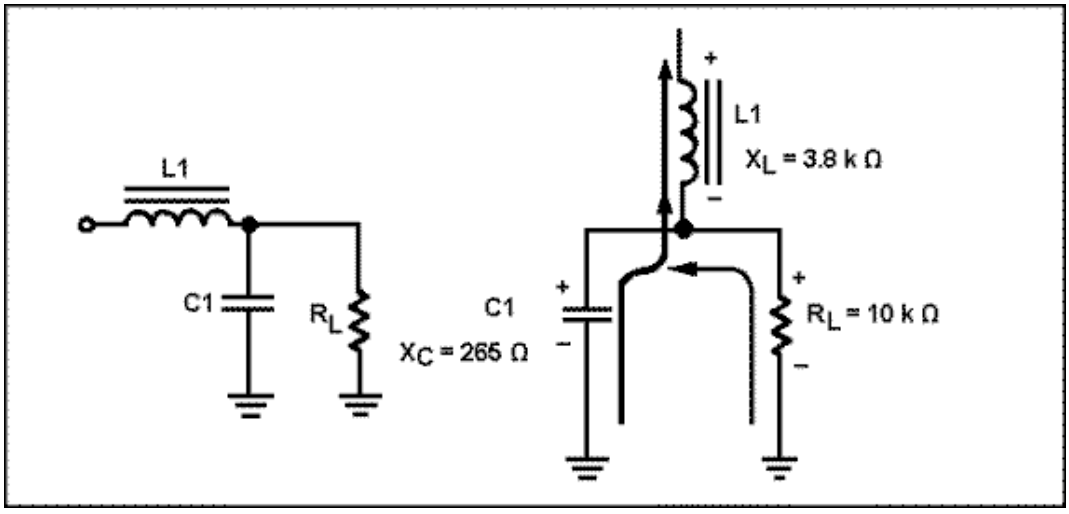

Figure 3-33. Alternating Current Component in an LC Choke Input Filter.

You now have a voltage divider as illustrated in figure 3-34. Because of the impedance ratios, a large amount of ripple voltage is dropped across L1, and

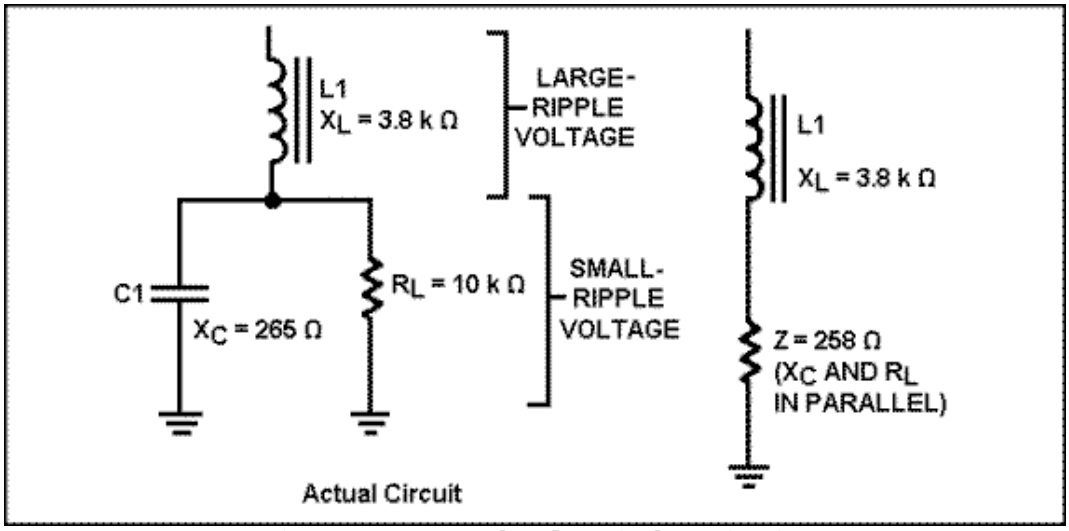

Figure 3-34. Actual and Equivalent Circuits.

a substantially smaller amount is dropped across C1 and RL. You can further increase the ripple voltage across L1 by increasing the inductance:

$$X_L = 2\eta fL$$

A capacitor offers an infinite (∞) impedance to the flow of direct current. The dc component, therefore, must flow through R_L and L1. As far as the dc is concerned, the capacitor does not exist. The coil and the load are, therefore, in series with each other. The dc resistance of the filter choke is very low (50 ohms average). Therefore, most of the dc component is developed across the load, and a very small amount of the dc voltage is dropped across the coil, as shown in figure 3-35.

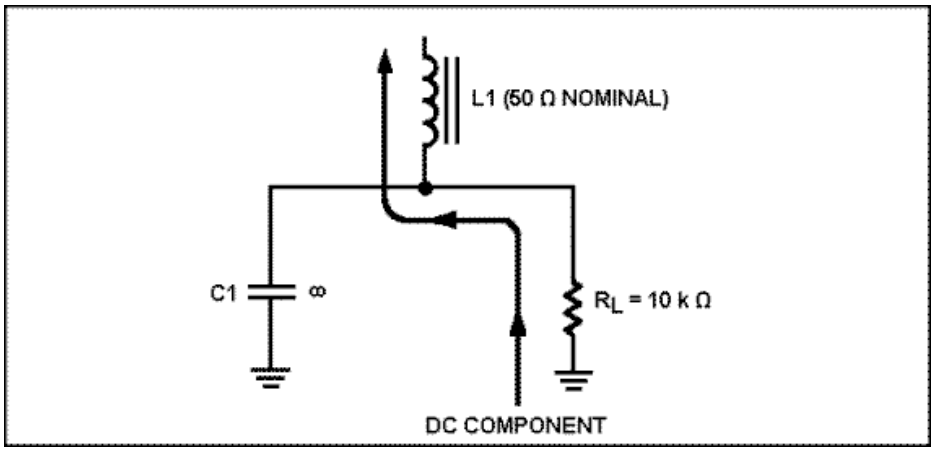

Figure 3-35. Direct Current Component in an LC Choke Input Filter.

Both the ac and the dc components flow through L1, and because the coil is frequency sensitive, it provides a large resistance to ac and a small resistance to dc. In other words, the coil opposes any changes in current. This property makes the coil a highly desirable filter component. Note that the filtering action of the LC capacitor input filter is improved when the filter is used in conjunction with a full-wave rectifier as shown in figure 3-36. This is due to a decrease in the X_C of the filter capacitor and an increase in the X_L of the choke. Ripple frequency of a full-wave rectifier is twice that of a half-wave rectifier. For a 60-hertz input, the ripple is 120 hertz. To calculate the X_C of C1 and the X_L of L1:

C1 and the X_L of L1:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{(2)(3.14)(120)(10)(10^{-6})}$$

$$X_C = \frac{(1)\ (10^6)}{7536}$$

$$X_C = 132.5\ \Omega$$

$$X_L = 2\pi fL$$

$$X_L = (2)(3.14)(120)(10)$$

$$X_L = 7.5 \text{ kilohms}$$

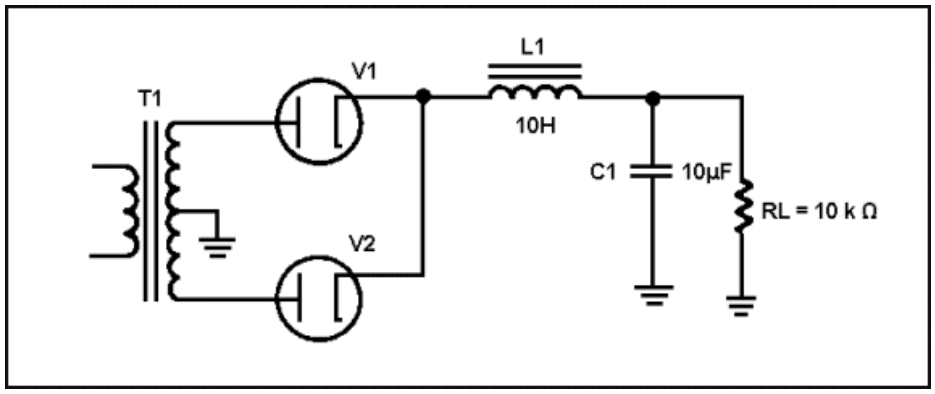

Figure 3-36. Full-wave Rectifier With an LC Choke Input Filter.

When the X_C of a filter capacitor is decreased, it provides less opposition to the flow of ac. The greater the ac flow through the capacitor, the lower the flow through the load. Conversely, the larger the X_L of the choke, the greater the amount of ac ripple developed across the choke; consequently, less ripple is developed across the load. Better filtering is thus obtained.

The filter capacitors are subject to open circuits, short circuits, and excessive leakage; the series inductor is subject to open windings and, occasionally, shorted turns or a short circuit to the core.

The filter capacitor in the choke input filter circuit is not subject to extreme voltage surges because of the protection offered by the inductor; however, the capacitor can become open, leaky, or shorted. Shorted turns in the choke may reduce the value of inductance below the critical value. This will result in excessive peak-rectifier current, accompanied by an abnormally high-output voltage, excessive ripple amplitude, and poor-voltage regulation. A choke winding that is open or a choke winding that is shorted to the core will result in a no-output condition. A choke winding that is shorted to the core may cause overheating of the rectifier element(s), blown fuses, etc.

With the supply voltage removed from the input to the filter circuit, one terminal of the capacitor can be disconnected from the circuit. The capacitor should be checked with a capacitance analyzer to determine its capacitance and leakage resistance. When the capacitor is electrolytic, you must use the correct polarity at all times. A decrease in capacitance or losses within the capacitor can decrease the efficiency of the filter and produce excessive ripple amplitude. If a suitable capacitance analyzer is not available, you can use an ohmmeter to check for leakage resistance. The test procedure is the same as that described for the input capacitor filter.

So far, this section has discussed in detail the operation and troubleshooting of the basic inductive and capacitive filter circuits. In the two remaining types of filters, only the differences between them and the other basic filters will be discussed.

Resistor-Capacitor (RC) Filters. The RC capacitor input filter is limited to applications in which the load current is small. This type of filter is used in power supplies where the load current is constant and voltage regulation is not necessary. For example, RC filters are used in high-voltage power supplies for cathode ray tubes and as part of decoupling networks for multistage amplifiers.

Figure 3-37 shows an RC capacitor input filter and associated waveforms. Both half-wave and full-wave rectifiers are used to provide the inputs. The RC filter in figure 3-37 consists of an input filter capacitor (C1), a series resistor (R1), and an output filter capacitor (C2). Although not part of the RC filter, R_L is shown to help explain the circuit. This filter is sometimes referred to as an RC pi-section filter because its schematic symbol resembles the Greek letter π.

Although the single capacitor filter is suitable for many noncritical, lowcurrent applications, when the load resistance is very low or when the percent of ripple must be held to an absolute minimum, the capacitor value

required must be extremely large. While electrolytic capacitors are available in sizes up to 10,000 F or greater, the larger sizes are expensive. A more practical approach is to use a more sophisticated filter that can do the same job but that has lower capacitor values, such as the RC filter.

The waveforms shown in view A of figure 3-37 represent the unfiltered output from a typical rectifier circuit. Note that the broken line, which indicates the average value of output voltage (E_{avg}) for the half-wave rectifier, is less than half the amplitude of the voltage peaks (approximately0.318). The average value of output voltage (Eavg) for the full-wave rectifier is greater than half (approximately 0.637), but is still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

An RC filter, such as a pi-section filter, does a better job than a single capacitor filter. Figure 3-37 illustrates an RC filter connected across the output of a rectifier. C1 performs exactly the same function as it did in the single capacitor filter. It is used to reduce the percentage of ripple to a relatively low value. Thus, the voltage across C1 might consist of an average dc value of +100 volts with a ripple voltage of 10 volts, as shown in view B. This voltage is passed on to the R1-C2 network, which reduces the ripple even further (view C).

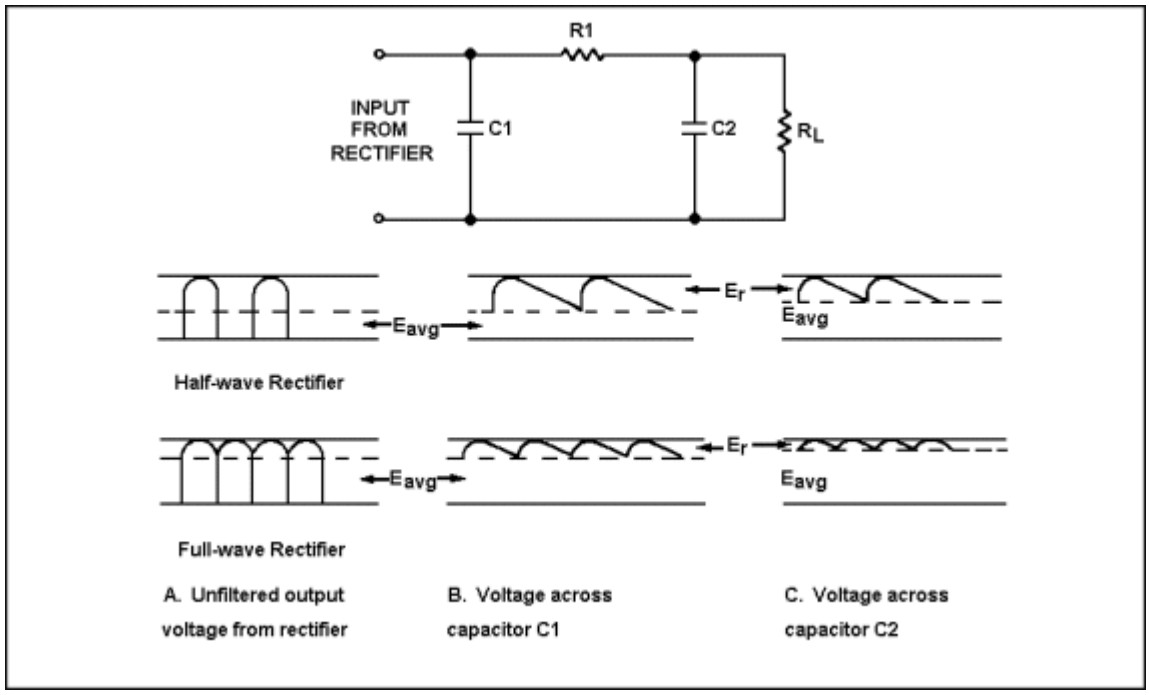

Figure 3-37. RC Filter and Waveforms.

C2 offers an infinite impedance (resistance) to the dc component of the output voltage. Thus, the dc voltage is passed to the load but reduces in value by the amount of the voltage drop across R1. However, R1 is generally small compared to the load resistance. Therefore, the drop in the dc voltage by R1 is not a drawback.

Component values are designed so that the resistance of R1 is greater than the reactance of C2 at the ripple frequency. C2 offers a very low impedance to the ac ripple frequency. Thus, the ac ripple senses a voltage divider consisting of R1 and C2 between the output of the rectifier and ground. Therefore, most of the ripple voltage is dropped across R1. Only a trace of the ripple voltage can be seen across C2 and the load.

In extreme cases where the ripple must be held to an absolute minimum, a second stage of RC filtering can be added. In practice, the second stage is rarely required. The RC filter is extremely popular because smaller capacitors can be used with good results.

The RC filter has some disadvantages. First, the voltage drop across R1 takes voltage away from the load. Second, power is wasted in R1 and is dissipated in the form of unwanted heat. Finally, if the load resistance changes, the voltage across the load changes. Even so, the advantages of the RC filter overshadow these disadvantages in many cases.

The shunt capacitors (C1 and C2) are subject to an open circuit, a short circuit, or excessive leakage. The series filter resistor (R1) is subject to changes in value and occasionally opens. Any of these troubles can be easily detected.

The input capacitor (C1) has the greatest pulsating voltage applied to it and is the most susceptible to voltage surges. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The remaining shunt capacitor (C2) in the filter circuit is not subject to voltage surges because of the protection offered by the series filter resistor (R1). However, a shunt capacitor can become shorted, open, or leaky.

A shorted capacitor or an open filter resistor results in a no-output indication. An open filter resistor results in an abnormally high dc voltage at the input of the filter. Leaky capacitors or filter resistors that have lost their effectiveness or filter resistors that have decreased in value result in an excessive ripple amplitude in the output of the supply.

LC Input Filter. The LC input filter is one of the most commonly used filters. This type of filter is used primarily in radio receivers, small audio amplifier power supplies, and in any type of power supply where the output current is low and the load current is relatively constant. Figure 3-38 shows an LC input filter and associated waveforms. Both half-wave and full-wave rectifier circuits are used to provide the inputs.

The waveforms shown in view A of figure 3-38 represent the unfiltered output from a typical rectifier circuit. Note again that the average value of output voltage ($E_{avg)}$ for the half-wave rectifier is less than half the amplitude of the voltage peaks. This is indicated by the broken line. The average value of output voltage (E_{avg}) for the full-wave rectifier is greater than half, but is

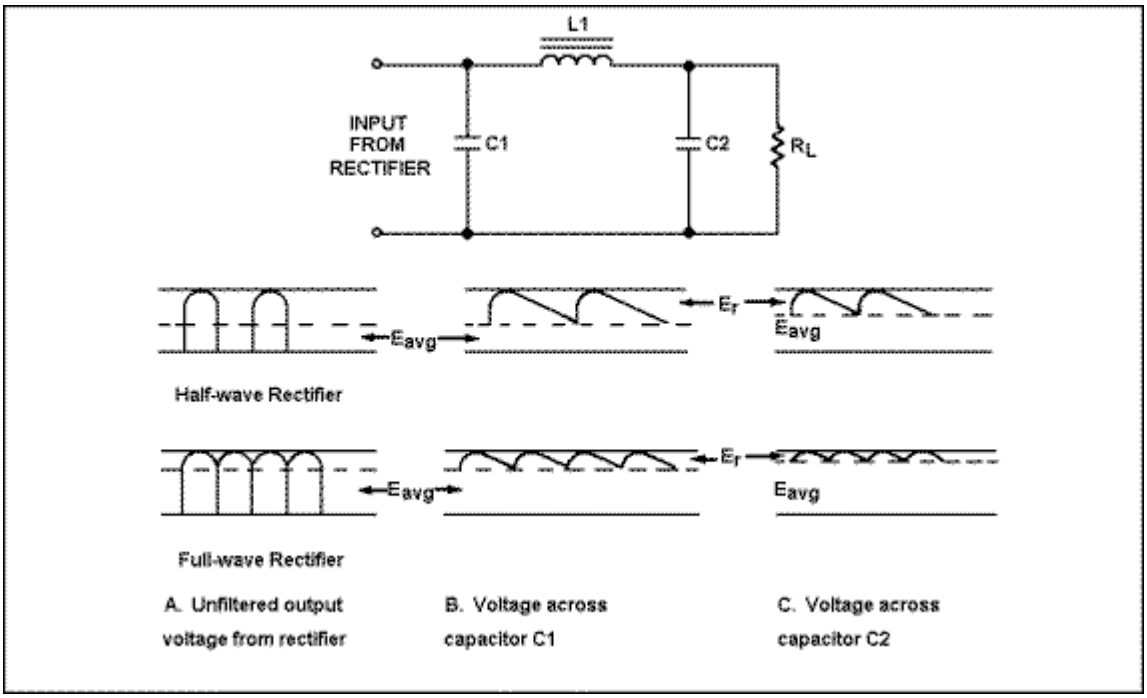

Figure 3-38. LC Capacitor Input Filter and Waveforms.

still much less than the peak amplitude of the rectifier-output waveform. With no filter circuit connected across the output of the rectifier circuit (unfiltered), the waveform has a large value of pulsating component (ripple) as compared to the average (or dc) component.

A common type of LC filter is shown in figure 3-38. C1 performs the same functions as discussed earlier by reducing the ripple to a relatively low level as shown in view B. L1 and C2 form the LC filter that reduces the ripple even further (view C).

L1 is a large value iron-core inductor (choke). It has a high value of inductance and, therefore, a high value of X_L that offers a high reactance to the ripple frequency. At the same time, C2 offers a very low reactance to the ac ripple. L1 and C2 form an ac voltage divider and because the reactance of L1 is much higher than that of C2, most of the ripple voltage is dropped across L1. Only a slight trace of the ripple appears across C2 and the load. While the L2-C2 network greatly reduces the ac ripple, it has little effect on the dc. An inductor offers no reactance to dc. The only opposition to current flow is the resistance of the wire in the choke. Generally, this resistance is very low and the dc voltage drop across the coil is minimal. Thus, the LC filter overcomes the disadvantages of the RC filter.

Aside from the voltage divider effect, the inductor improves filtering in another way. An inductor resists changes in the magnitude of the current flowing through it. Consequently, when the inductor is placed in series with the load, the inductor tends to hold the current steady. In turn, this helps to hold the voltage across the load constant.

The LC filter provides good filtering action over a wide range of currents. The capacitor filters best when the load is drawing little current. Thus, the capacitor discharges very slowly and the output voltage remains almost constant. On the other hand, the inductor filters best when the current is highest. The complementary nature of these components ensures good filtering over a wide range of current when size of components is a factor.

The LC filter has two disadvantages. First, it is more expensive than the RC filter because an iron-core choke costs more than a resistor. The second disadvantage is its size: the iron-core choke is both bulky and heavy. Thus, the LC filter may be unsuitable for some applications but is still one of the most widely used.

Shunt capacitors are subject to open circuits, short circuits, and excessive leakage; series inductors are subject to open windings and occasionally shorted turns or a short circuit to the core. The input capacitor (C1) has the greatest pulsating voltage applied to it, is the most susceptible to voltage surges, and has a generally higher average voltage applied. As a result, the input capacitor is frequently subject to voltage breakdown and shorting. The output capacitor (C2) is not as susceptible to voltage surges because of the series protection offered by the series inductor (L1), but the capacitor can become shorted, open, or leaky.

A shorted capacitor, an open filter choke, or a choke winding that is shorted to the core results in a no-output indication. A shorted capacitor, depending on the magnitude of the short, may cause a shorted rectifier, transformer, or filter choke that results in a blown fuse in the primary of the transformer.

An open filter choke results in an abnormally high dc voltage at the input to the filter and no voltage at the output of the filter. A leakage or open capacitor in the filter circuit results in a low dc output voltage. The condition is generally accompanied by an excessive ripple amplitude. Shorted turns in the winding of a filter choke reduce the effective inductance of the choke and decrease its filtering efficiency. As a result, the ripple amplitude increases.

Regulators

Ideally, the output of most power supplies should be a constant voltage. Unfortunately, this is difficult to achieve. There are two factors that can cause the output voltage to change. First, the ac line voltage is not constant. The so-called 115 volts ac can vary from about 105 volts ac to 125 volts ac. This means that the peak ac voltage alone can be responsible for a nearly 20 percent change in the dc output voltage. The second thing that can change the dc output voltage is a change in the load resistance. In complex electronic equipment, the load can change as circuits are switched in and out. In a television receiver, the load on a particular power supply may depend on the brightness of the screen, the control settings, or even the channel selected. These variations in load resistance tend to change the applied dc voltage because the power supply has a fixed internal resistance. If the load resistance decreases, the internal resistance of the power supply drops more voltage. This causes a decrease in the voltage across the load.

Many circuits are designed to operate with a particular supply voltage. When the supply voltage changes, the operation of the circuit may be adversely affected. Consequently, some types of equipment must have power supplies that produce the same output voltage regardless of changes in the load resistance or changes in the ac line voltage. This constant power supply may be achieved by adding a circuit called the voltage regulator at the output of the filter. There are many different types of regulators in use today; to discuss all of them would be beyond the scope of this course.

A commonly used figure of merit for a power supply is its percent of regulation. The figure of merit gives us an indication of how much the output voltage changes over a range of load resistance values. The percent of regulation aids in the determination of the type of load regulation needed. Percent of regulation is determined by the equation:

$$\text{Percent of Regulation} = \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100$$

This equation compares the change in output voltage at the two loading extremes to the voltage produced at full loading. For example, assume that a power supply produces 12 volts when the load current is zero. If the output voltage drops to 10 volts when full load current flows, then the percent of regulation is:

$$\begin{aligned}\text{Percent of Regulation} &= \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100 \\ &= \frac{12-10}{10} \times 100 \\ &= \frac{2}{10} \times 100 \\ &= 20\%\end{aligned}$$

Ideally, the output voltage should not change over the full range of operation. A 12-volt power supply should produce 12 volts at no load, at full load, and at all points in between. In this case, the percent of regulation would be:

$$\begin{aligned}\text{Percent of Regulation} &= \frac{E_{\text{no load}} - E_{\text{full load}}}{E_{\text{full load}}} \times 100 \\ &= \frac{12-12}{12} \times 100 \\ &= \frac{0}{12} \times 100 \\ &= 0\%\end{aligned}$$

Thus, zero-percent load regulation is the ideal situation. It means that the output voltage is constant under all load conditions. While you should strive for zero-percent load regulation, in practical circuits you must settle for something less. Even so, by using a voltage regulator, the percent of regulation can be held to a very low value.

The output of a power supply varies with changes in input voltage and circuit load current requirements. Because much of the military's electronic equipment requires operating voltages and currents that must remain constant, some form of regulation is necessary. The circuits that maintain power supply voltage or current outputs within specified limits, or tolerances, are called regulators. They are designated as dc voltage or dc current regulators depending on their specific application.

Voltage regulator circuits are additions to basic power supply circuits that are made up of rectifier and filter sections. The purpose of the voltage regulator is to provide an output voltage with little or no variation. Regulator circuits sense changes in output voltages and compensate for the changes. Regulators that maintain voltages within plus or minus (±) 0.1 percent are quite common. The diagram in figure 3-39 illustrates the purpose of the voltage regulator.

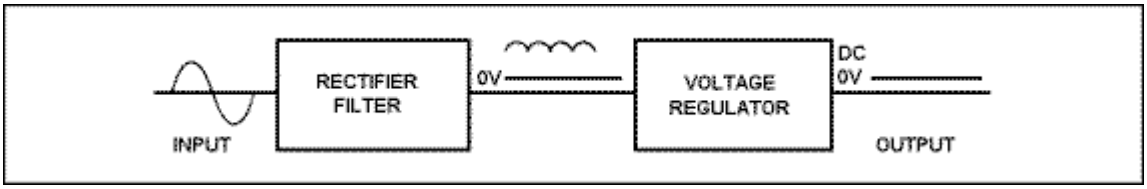

Figure 3-39. Block Diagram of a Power Supply and Regulator.

There are two basic types of voltage regulators. Voltage regulators are classified as series or shunt, depending on the location or position of the regulating element(s) in relation to the circuit load resistance. Figure 3-40 illustrates the two basic types of voltage regulators. In actual practice the circuitry of regulating devices may be quite complex. The simplified drawings shown in the figure are presented to emphasize that there are two basic types of voltage regulators. Broken lines have been used to highlight the differences between the series and shunt regulators.

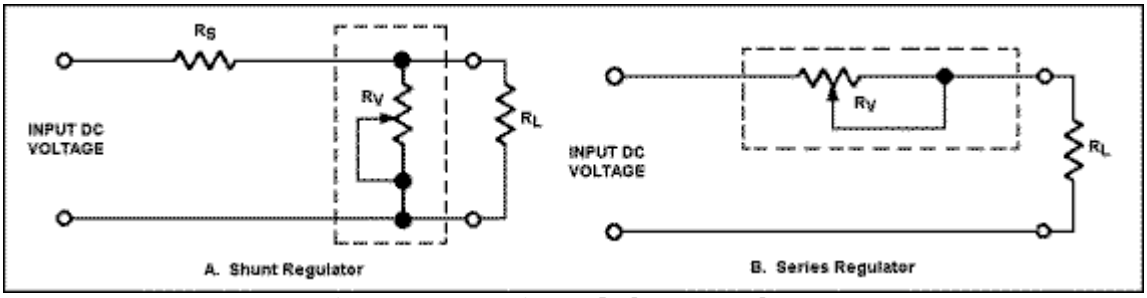

Figure 3-40. Series and Shunt Regulators.

The schematic in view A is that of a shunt-type regulator. It is called a shunt-type regulator because the regulating device is connected in parallel with the load resistance. This is a characteristic of all shunt-type regulators. The schematic in view B is that of a series regulator. It is called a series regulator because the regulating device is connected in series with the load resistance.

Series Voltage Regulator. Figure 3-41 illustrates the principle of series voltage regulation. Note that the regulator is in series with the load resistance and that all current passes through the regulator. In this example variable resistor R_V is used for regulation. Examine the circuit to determine how the regulator functions. When the input voltage increases, the output voltage also increases. However, since the voltage regulator device (R_V) senses this change, the resistance of the regulating device increases and results in a greater voltage drop across R_V. This causes the output voltage to decrease to normal or, for all practical purposes, to remain constant.

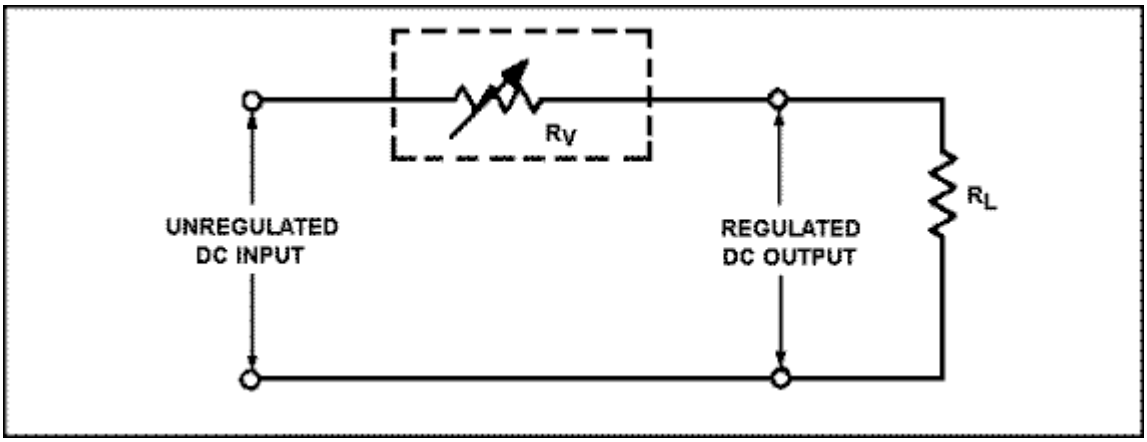

Figure 3-41. Series Voltage Regulator.

As the input voltage decreases, the resistance of the variable resistor R_V decreases almost simultaneously, thereby compensating for the voltage drop. Since there is a smaller voltage drop across R_V, the output voltage remains almost constant. Voltage fluctuations within the circuit occur in microseconds.

Shunt Voltage Regulator. The diagram in figure 3-42 represents a shunt voltage regulator. Note that variable resistor R_V is in parallel with the load resistance R_L and that fixed resistor R_S is in series with the load resistance. The voltage drop across a fixed resistor remains constant unless there is a variation (increase or decrease) in the current following through it.

In a shunt voltage regulator as shown in figure 3-42, output voltage regulation is determined by the current flowing through the parallel resistances of the regulating device (R_V), the load resistance (R_L), and the series resistor (R_S). For now, assume that the circuit in 3-42 is operating under normal conditions, that the input is 120 volts dc, and that the desired regulated output is 100 volts dc. For a 100-volt output to be maintained, 20 volts must be dropped across the series resistor (R_S). If you assume that the value of R_S is 2 ohms, then there must be 10 amperes of current across R_V and R_L (E = IR). If the values of the resistance of R_V and R_L are equal, then 5 amperes of current will flow through each resistance (R_V and R_L).

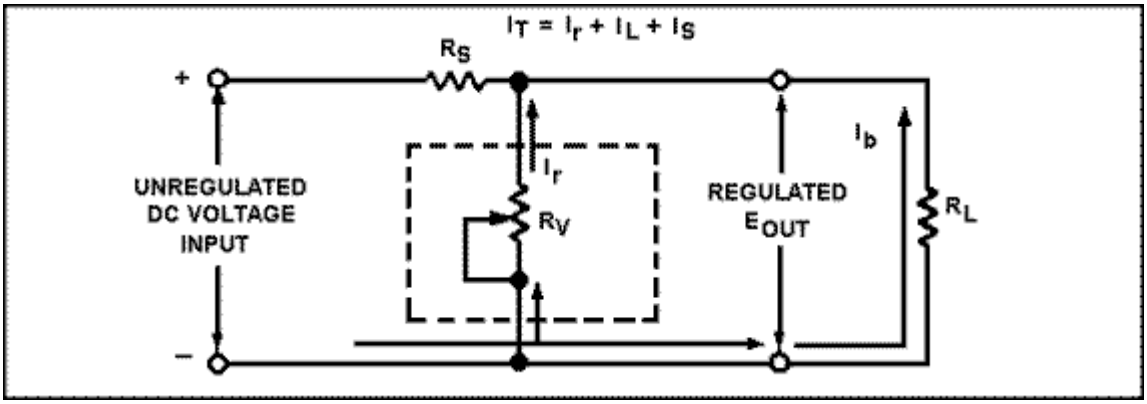

Figure 3-42. Shunt Voltage Regulator.

If the load resistance (R_L) increases, the current through R_L will decrease. For example, assume that the current through R_L is now 4 amperes and that the total current across R_S is 9 amperes. With this drop in current, the voltage drop across R_S is 18 volts; consequently, the output of the regulator has increased to 102 volts. At this time, the regulating device (R_V) decreases in resistance, and 6 amperes of current flow through this resistance (R_V). Thus, the total current across R_S is once again 10 amperes (6 amperes across R_V, 4 amperes across R_L); therefore, 20 volts will be dropped across R_S causing the output to decrease back to 100 volts.

If the load resistance (R_L) increases, the regulating device (R_V) decreases its resistance to compensate for the change. If R_L decreases, the opposite effect will occur and R_V will increase.

When R_L decreases, the current through R_L subsequently increases to 6 amperes. This action causes a total of 11 amperes to flow through R_S, which now drops 22 volts. As a result, the output is now 98 volts. However, the regulating device (R_V) senses this change and increases its resistance so that less current (4 amperes) flows through R_V. The total current again becomes 10 amperes, and the output is again 100 volts. The shunt regulator maintains the desired output voltage by sensing the current change that occurs in the parallel resistance of the circuit.

Refer to the schematic shown in figure 3-42 and consider how the voltage regulator operates to compensate for changes in input voltages. The input voltage may vary and any variation must be compensated for by the regulating device. Consider an increase in input voltage. When this happens, the resistance of R_S automatically decreases to maintain the correct voltage division between R_F and R_S. You should see, therefore, that the regulator operates in the opposite way to compensate for a decrease in input voltage.

So far, the operation of voltage regulators that use variable resistors has been explained; however, this type of regulation has limitations. Obviously, the variable resistor cannot be adjusted rapidly enough to compensate for frequent fluctuations in voltages. Since input voltages fluctuate frequently and rapidly, the variable resistor is not a practical method for voltage regulation. A voltage regulator that operates continuously and automatically to regulate the output voltage without external manipulation is required.

Basic VR Tube Regulator Circuit. Table 3-1 gives the characteristics of common VR tubes. This table includes a column that shows the amount of regulation to be expected over the operating range of the tube. As can be seen, a variety of VR tubes is available. A common designation of VR tubes is the use of numbers, such as VR105-40. The letters indicate the function of the tube (voltage regulator). The numbers preceding the dash indicate the maximum current (in milliamperes) that may be allowed and still maintain regulation. The minimum supply voltage column indicates the lowest supply voltage that will ensure firing each time the supply is energized. The minimum value of current gain in the table is the current required to sustain operation within the normal glow discharge region. This current is sometimes called the "keep alive" current.

Table 3-1. Voltage Regulator Tube Ratings.

Type	*Operating Volts*	*Current*		*Minimum Supply*	*Regulated Voltage*
		Min	*Max*		
OA2	150	5	30	185	2
OA3-VR75	75	5	40	105	5
OB2	108	5	30	133	2
OB3-VR90	90	5	40	130	6
OC2	75	5	30	105	5
OC3-VR105	105	5	40	135	2
OD3-VR150	150	5	40	185	4
OG3	85	1	10	125	4
1B46	80	1	2	225	3

Figure 3-43 shows a basic VR tube regulating circuit. The voltage produced by the source is 150 volts. The VR90 will provide a constant 90 volts across the load resistance (R_L) if the tube is operated in the normal glow discharge region. This means that 60 volts is dropped across R_S, which is the series limiting resistance used to limit the current through the VR tube.

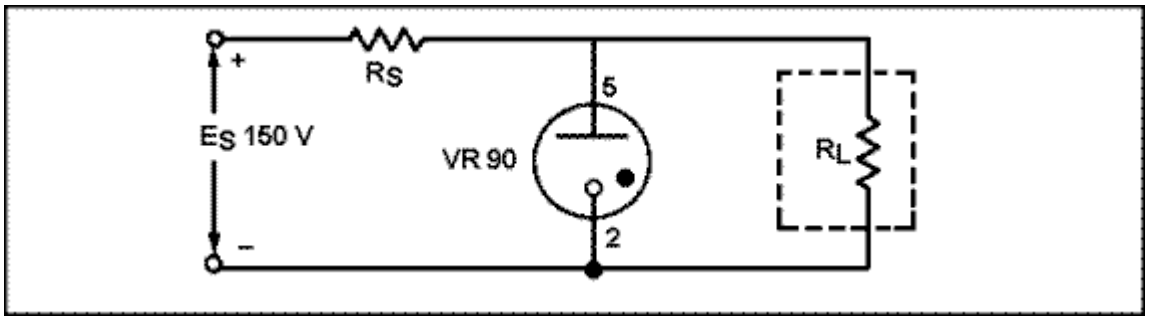

Figure 3-43. Basic VR Tube Regulator.

Since the operating limits of a VR tube are determined by its maximum and minimum currents, circuits using such tubes should be designed to allow maximum variations in current above and below the normal point of operation. The normal point of operation, which allows maximum variation in current, must be midway between the current limits of the tube. This median current is called I mean and can be calculated by the use of the following equation:

$$I_{mean} = \frac{I_{max} + I_{min}}{2}$$

The mean current for the VR90-40 as shown in figure 3-44 can be determined by using the following values:

$$I_{mean} = \frac{40 + 5}{2} = \frac{45}{2} = 22.5\ mA$$

To calculate the value of series dropping resistance R_S, the following equation can be used:

$$Rs = \frac{\text{Source Voltage - Regulated Voltage}}{I_{mean} + I_{load\ (average)}}$$

If the average current flowing through the load of figure 3-44 is 100 milliamperes, the series dropping resistance can be found in the following manner:

$$R_s = \frac{150 + 90}{22.5 + 100} = \frac{60\ \text{volts}}{122.5\ \text{mA}} = 490\ \text{ohms}$$

According to Ohm's law, the value of the load resistance for this circuit figure will be 900 ohms if a current of 100 milliamperes flows through R_L. The internal resistance of the VR tube can be calculated in a similar manner. With 22.5 milliamperes flowing and 90 volts dropped across the VR tube, its resistance is 4 kilohms.

To show voltage regulation in the circuit for figure 3-44, assume that there is a constant supply voltage of 150 volts and a variable load resistance. If the value of R_L were to decrease to 857 ohms, the load current would increase to approximately 105 milliamperes to maintain 90 volts across the load resistance. R_S must drop 60 volts. To do so requires a current of 122.5 milliamperes flowing through the series resistance. Since 105 milliamperes is now flowing through the load, the current through the VR tube must decrease from 22.5 milliamperes to 17.5 milliamperes.

The original load resistance was 900 ohms. Changes in this resistance will not occur instantaneously, but will require some time to vary from 900 ohms to a new value. As resistance of the load begins to decrease, load current begins to increase. The minute increase in load current flows through the series resistance R_S causing a slight increase in E_S. This slight increase in voltage across R_S results in the VR tube voltage dropping slightly. This slight drop in tube voltage causes a decrease in the ionization of the tube. As a result, less current flows through the tube.

Note that tube current can decrease only to a value of 5 milliamperes before deionization occurs. Therefore, the load current cannot exceed 117.5 milli amperes, for beyond this value, tube current becomes less than 5 milliamperes and regulation ceases.

If load resistance increases, load current decreases. This results in the VR tube current increasing to maintain a current of 122.5 milliamperes. The VR tube current can only increase to 40 milliamperes. Beyond this value of current, the tube enters the abnormal glow region and tube voltage increases. The upper limit of the VR tube current occurs when load current decreases to a value of 82.5 milliamperes. When load current drops below this value, the VR tube ceases to regulate the load voltage. Therefore, with a constant source voltage but variable load resistance, the limits of regulation are reached when current in the load exceeds 117.5 milliamperes or drops below 82.5 milliamperes.

The VR tube regulator can also compensate for changes in power supply voltage. Under these conditions, the load resistance will remain constant while power supply voltage will be variable. Refer to figure 3-44 for the following discussion.

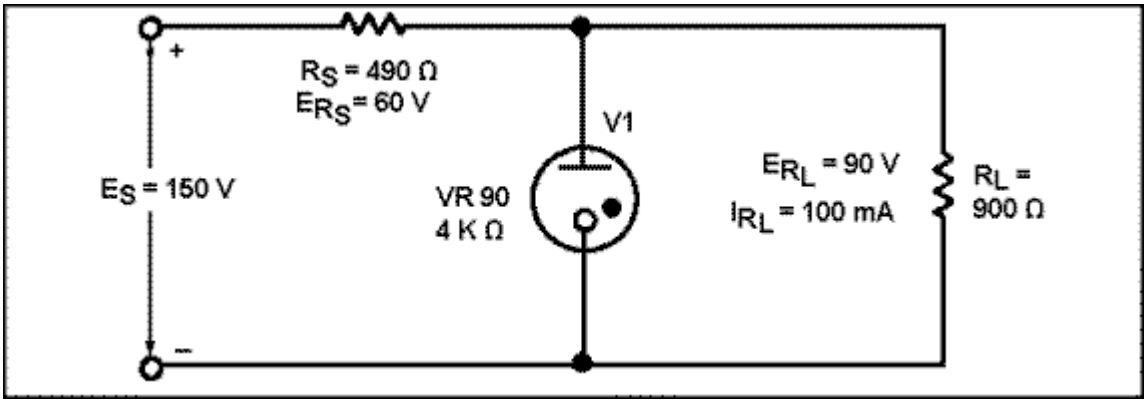

Figure 3-44. Simplified VR Tube Regulator.

Assume that the source voltage begins to increase from an original value of 150 volts toward 155 volts. As this voltage increases, current through R_S increases from its original value of 122.5 milliamperes. Initially, this additional current is drawn from the load, causing a slight increase in load voltage. This increase in load voltage is felt across the VR tube and causes an increase in tube ionization. This decreases the internal resistance of the VR tube with a resultant increase in tube current. When source voltage reaches 155 volts, current through R_S is approximately 133 milliamperes (R_S = 490 ohms). Most of the additional current through R_S flows through the VR tube. As a result, approximately 33 milliamperes flows through the VR tube, maintaining the load voltage at 90 volts.

Since VR tube current decreases as source voltage decreases, some point will be reached where tube current drops below its lower limit of 5 milliamperes. When source voltage drops below 141.4 volts, tube current will be less than 5 milliamperes and regulation will cease. The upper and lower limits of the supply voltage variations that can be allowed and still provide regulation in the circuit are 158.6 volts and 141.4 volts, respectively. Tube voltage varies slightly through its operating range, but this voltage change is less than that that would exist without the use of a VR tube.

As the source voltage increases, the current through the VR tube increases. Since the upper limit of tube current is 40 milliamperes, there is a limit in the ability of the tube to regulate increasing voltage. When the supply voltage exceeds 158.6 volts, tube current becomes greater than 40 milliamperes and regulation ceases.

If source voltage decreases from 150 volts to 145 volts, only 55 volts must be dropped across the 490-ohm series resistance (R_S) to enable load voltage to be maintained at 90 volts. Current through R_S for a 55-volt drop is 112 milliamperes. Since load current is 100 milliamperes, the remaining 12 milliamperes must flow through the VR tube. This represents a decrease in the ionization level of the VR tube with a resultant increase in tube resistance. Under these conditions, 90 volts will be maintained across the load resistance.

VR Tubes Connected in Series. In applications where a regulated voltage in excess of the maximum rating of one tube is required, two or more tubes may be placed in series as shown in figure 3-45.

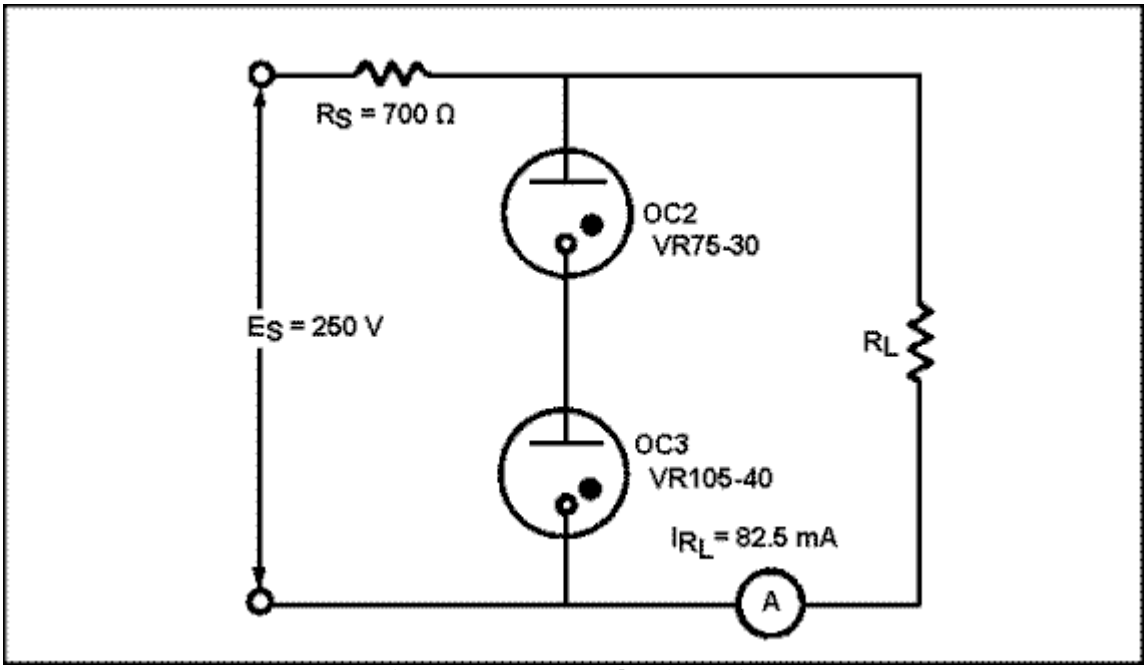

Figure 3-45. VR Tubes in Series.

In the figure a VR75-30 and VR105-40 are shown connected in series. The source voltage is 250 volts, and 82.5 milliamperes flows through the load resistance. Since current through the two VR tubes is common, the limits of regulation are determined by the tube having the smaller current limitations (in this case, the VR75-30). In computing I_{mean} for this circuit, I_{max} and I_{mean} are 30 milliamperes and 5 milliamperes, respectively. Therefore, the mean current is 17.5 milliamperes.

The value of R_S in the figure can be computed using the source voltage of 250 volts and the total current through R_S (load current + I_{mean}). When these values are used, R_S = 700 ohms. Note that the regulated voltage to the load is 180 volts. This provides a regulated voltage greater than would be possible using either VR tube by itself.

Another advantage of using VR tubes in series is illustrated in figure 3-46. In this circuit, several values of regulated voltages are obtained from a single power supply. The current flowing through V2 in the figure is a combination of the current through R1 and the current through V1. The current through V3, on the other hand, is the sum of the currents through V2 and R2. Since V3 has more current flowing through it than any of the other VR tubes, it places or determines the limit on the maximum current in the VR tube circuit. Since the maximum rating of V3 is 40 milliamperes, the current through R1 and R2 must be limited to only a few milliamperes, or the rating of V3 will be exceeded and regulation will cease.

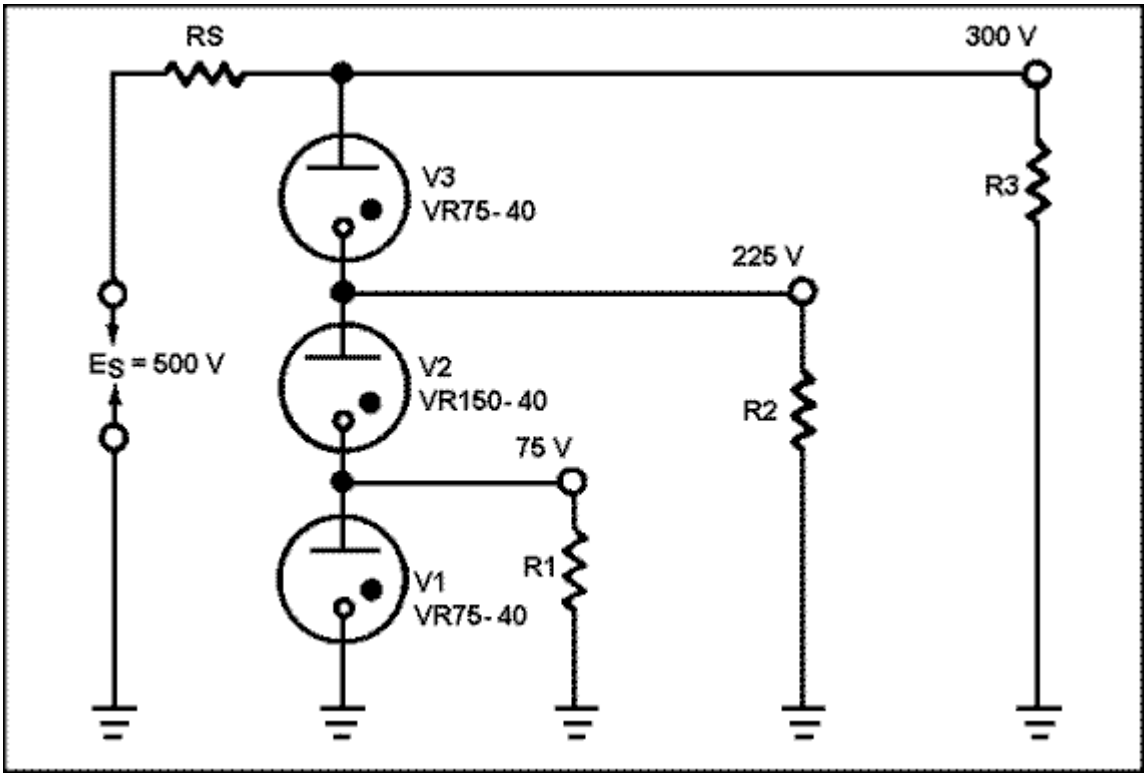

Figure 3-46. VR Tubes as Voltage Regulators.

The obvious advantage in using VR tubes in series is to provide several regulated voltages from a single power supply. The primary disadvantage is in the current limitations. Since it is impossible to have all VR tubes operating about their mean current values, this limits the ability of the circuit to regulate over wide ranges of variations in load resistance or source voltage.

VR Tubes Connected in Parallel. In some gas-filled tubes, connecting VR tubes in parallel as shown in figure 3-47 increases the current handling capacity of the network. This is not true of VR tubes. In figure 3-47, two VR tubes are constructed in exactly the same way. The only difference is a slight variation in their ionization potential. For the purpose of this discussion, VR tube VR1 will have a lower ionization potential than VR2. The potential that must be reached before a VR tube ionizes is considerably higher than its normal operating voltage.

When voltage is applied to the circuit of figure 3-47, as soon as the correct potential is reached, VR1 begins to conduct and the potential across it decreases to its operating voltage. The potential across VR2 never becomes sufficiently high enough to cause it to ionize.

Therefore, placing the VR tubes in parallel accomplishes no useful purpose. When greater current handling capacity and better regulation are desired, electronic (vacuum tube) regulator circuits are used.

Initially, some indication of the trouble associated with a gas-tube regulator circuit can be obtained by visual inspection to determine the presence of the characteristic glow from the ionized gas within the tube. When current through the tube is near its maximum rating, the tube is highly ionized; when the current is near its minimum rating, the tube is lightly ionized; therefore, the intensity of the gaseous discharge within the tube is an indication of tube condition. If the tube is not ionized, however, this does not necessarily mean that the tube is defective. The same indication (lack of characteristic glow) may possibly occur if the following indications are observed: the series resistor (R_S) increases in value, the dc input voltage (E_S) is below normal, and the load current is excessive. It is therefore necessary to make dc voltage measurements at the input and output terminals of the voltage regulator circuit to determine whether the fault lies within the regulator circuit or whether it is external to the regulator circuit.

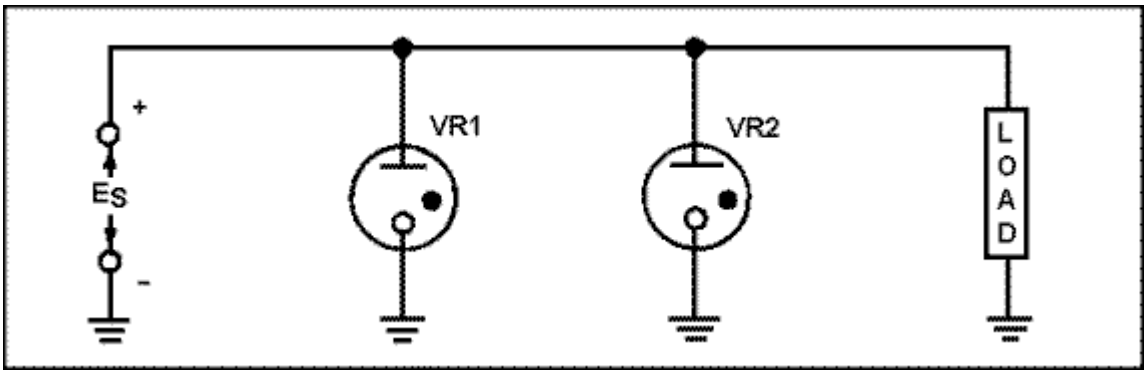

Figure 3-47. VR Tubes Connected in Parallel.

The value of the series resistor (R_S) can be checked by ohmmeter measurements to determine whether any change in resistance has occurred. If the maximum current rating of the regulator tube is exceeded for a considerable length of time, the tube may be damaged and lose its regulation characteristics; therefore, the regulator tube itself can be suspected as a possible source of trouble.

Although VR tubes are used extensively in electronic equipment, there are circuits that require a greater degree of regulation than a VR tube can provide. For this reason an electron tube voltage regulator is used.

Electron Tube Voltage Regulator. An electron tube may be considered as a variable resistance. When the tube is passing a direct current, this resistance is simply the plate-to-cathode voltage divided by the current through the tube and is called the dc plate resistance (R_p). For a given plate voltage, the value of R_p depends upon the tube current, and the tube current depends upon the grid bias.

Refer to figure 3-48, view A. The resistance of V1 is established initially by the bias on the tube. Assume that the voltage across the load is at the desired value. Then the cathode is positive with respect to ground by some voltage (E_L). The grid can be made positive relative to ground by a voltage (E2) that is less than E1. The potentiometer R2 is adjusted until the bias (grid-to-cathode voltage), which is E2-E1, is sufficient to allow V1 to pass a current equal to the desired load current. With this bias, the resistance of V1 is established at the proper value to reduce the rectifier output voltage to the desired load voltage.

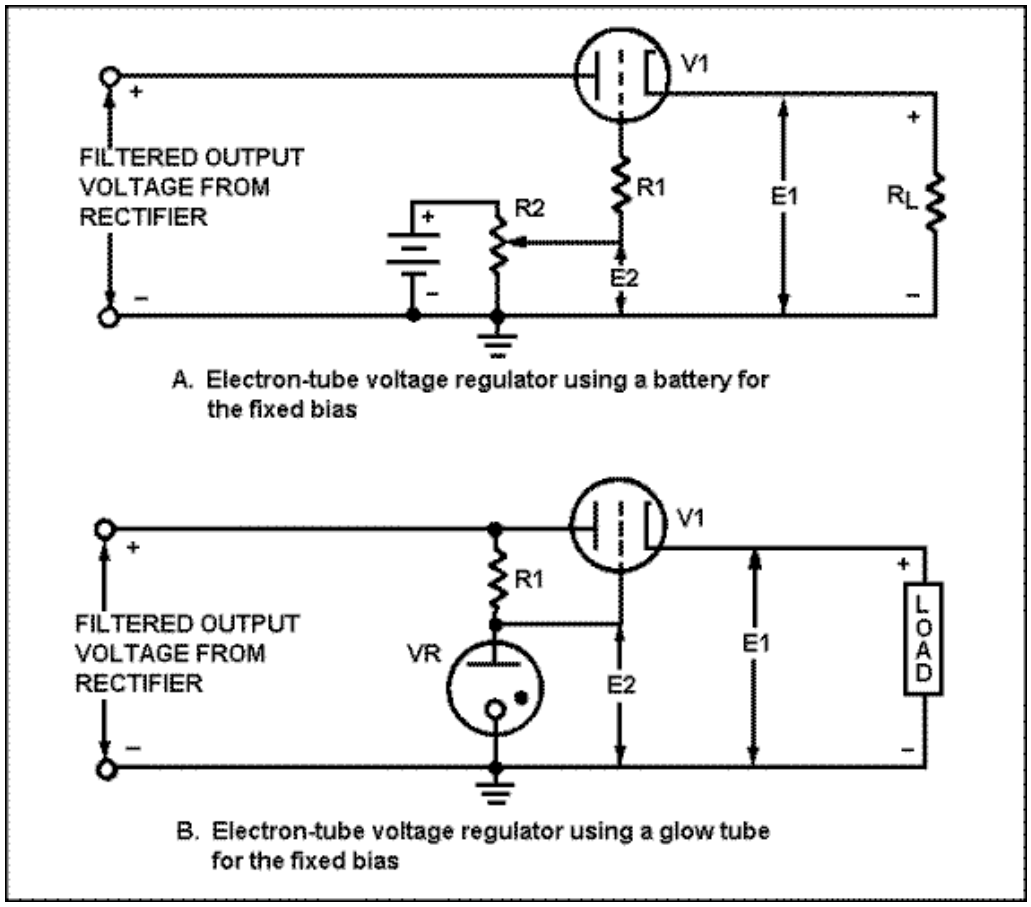

Figure 3-48. Electron Tube Voltage Regulator.

If the rectifier output voltage increases, the voltage at the cathode of V1 tends to increase. As E1 increases, the negative bias on the tube increases and the plate resistance of the tube becomes greater. Consequently, the voltage drop across V1 increases with the rise in input voltage. If the circuit is properly designed, the increase in voltage drop across V1 is approximately equal to the increase in voltage at the input. Thus, the load voltage remains essentially constant.

The resistor (R1) is used to limit the grid current. This is necessary in this particular circuit because the battery is not disconnected when the power is turned off. However, the battery can be eliminated from the circuit by the use of a glow tube (V2), as shown in view B of the figure, to supply a fixed bias for the grid of the tube. The action of the circuit in view B is the same as the action of the circuit in view A. The output voltage of the simple voltage regulators shown in the figure cannot remain absolutely constant. As the rectifier output voltage increases, the voltages on the cathode of V1 must rise slightly if the regulator is to function.

The voltage regulators shown in the figure compensate not only for changes in the output voltage from the rectifier but also for changes in the load. For example, in view B if the load resistance decreases, the load current will increase. The load voltage will tend to fall because of the increased drop across V1. The decrease in load voltage is accompanied by a decrease in bias voltage on V1. The bias voltage on V1 is equal to E1-E2. Thus the effective resistance of V1 is reduced at the same time the load current is increased. The IR drop across V1 increases about as much as I increases. Therefore, the tendency for the load voltage to drop when the load is increased is checked by the decrease in resistance of the series triode.

In most power supplies, current is not directly regulated. Fuses and other circuit protection devices are used to set an upper limit to the amount of current that can flow in a power supply. Once this limit is exceeded, the fuse simply opens and the power supply is de-energized. Beyond this, current is usually left unregulated because the load will draw from the power supply only the amount of current that it needs. Decreases and increases in the power supply voltage caused by variations in load current are usually controlled by the voltage regulator.

There are some cases where current must be regulated or kept at a relatively constant value. The best example of this is the filament supply of a power transformer located in a power supply that is designed to supply filament power to many tubes. (See view A of figure 3-49, which is a portion of a power supply designed to supply 50 vacuum tubes with both plate and filament voltages.) Under normal conditions, circuit current will not exceed 2.5 amperes. For this reason, the power supply has been fused at 3 amperes. Only the portion of the power supply that deals with current regulation is shown, namely the power transformer and 4 of the 50 parallel connected vacuum-tube filaments. At operating temperatures, the resistance of each filament is 1 kilohm. Because the filaments are connected in parallel, the total filament resistance at operating temperature is 20 ohms. Ohm's law, $I = \frac{E}{R}$ tells you that/the filaments draw .315 amperes. As conductors are heated, their resistance increases. Therefore, the cold resistance of the filaments is considerably lower than the hot resistance. In this case, assume there are 100 ohms per filament. The total resistance of the 50 parallel filaments is then 2 ohms when the power supply is first energized, and the filaments draw 3.15 amperes of current. If the current for the rest of the power supply is added to the filament current, the surge current will cause the power supply to draw 5 amperes when it is first energized. Unfortunately, the power supply is fused at 3 amperes. Under these conditions, it would be impossible to keep the power supply on the line long enough to get the filaments up to operating temperature.

There are three possible solutions to this problem. The first is simply to fuse the power supply at 5 amperes, but this could allow excessive current to flow in the power supply. Another solution is to use a slow-blow fuse. Unfortunately, the duration of the current surge may exceed the time limit that a slow-blow fuse can handle. Therefore, current regulation is the best solution to this problem. Because of its quick-heating ability, the amperite tube is ideal as a current regulator. The amperite regulator is nothing more than an iron wire enclosed in a hydrogen-filled envelope. Because of its construction, the iron filament will heat quickly when current is applied to it.

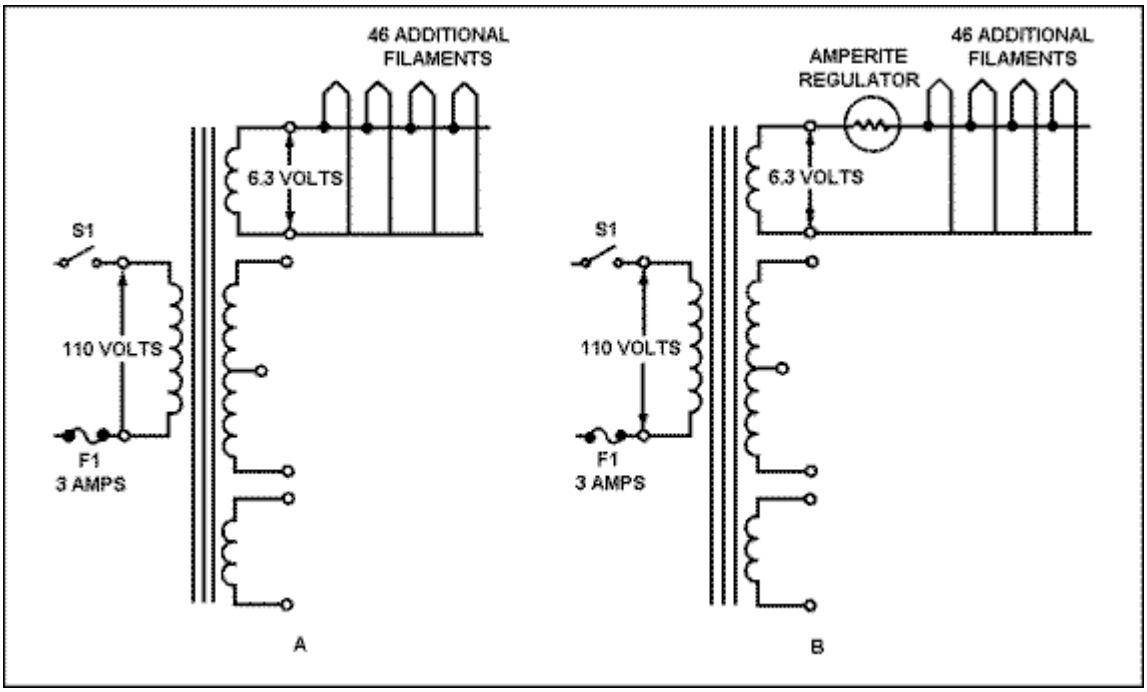

Figure 3-49. Amperite Regulator.

View B of figure 3-49 shows the amperite regulator connected in series with the filaments of the load. When the power supply is first energized, the iron wire of the amperite gets hot quickly and presents a large resistance connected in series with the 2 ohms of filament resistance. As a result, most of the voltage is dropped across the amperite. Because of the large resistance of the amperite regulator, current in the circuit is held to an acceptable level in accordance with Ohm's law.

As the filaments warm up, their resistance increases, a fact that causes circuit current to decrease. The decreasing circuit current allows the iron wire of the amperite to cool. As it cools, its resistance decreases until the approximate resistance of the circuit wiring is reached. As the iron wire of the amperite cools and its resistance decreases, the resistance of the warming tube filaments increases. Throughout the entire heating cycle of the filaments, the total resistance of the series circuit, consisting of the amperite and tube filaments, remains fairly constant. When power is first applied, most of the resistance is in the amperite. Therefore, most of the voltage is dropped across the resistance of the amperite. Halfway through the cycle, the resistance of the amperite and the resistance of the filaments can become approximately equal, and the voltage that drops across the two series elements is equal. Finally, when the filaments have reached their operating temperature, most of the resistance is in the filaments of the tube. Therefore, most of the voltage is dropped across the tube filaments.

The important thing to note is that the total circuit resistance remains approximately the same throughout the heating cycle. As the cycle progresses, the resistance of the amperite decreases as the resistance of the filaments increases. Because resistance and voltage (6.3 volts) remain constant, current remains constant except for the slight surge in the beginning of the heating cycle that is necessary to heat up the iron wire of the amperite.

TROUBLESHOOTING POWER SUPPLY

When working with electricity, the proper use of safety precautions is one of the most important things to remember. There is a section on safety precautions in the front of all electronic technical manuals. Also, specific precautions should be posted on each piece of electronic equipment. One hazardous area that is sometimes overlooked is the method in which equipment is grounded. By grounding the return side of the power transformer to the metal chassis, the cathode of the tubes in both the power supply and the load being supplied by the power supply can be wired directly to the metal chassis. Therefore, the necessity of wiring each tube directly to the return side of the transformer is eliminated. This method saves wire and reduces the cost of building the equipment. While this solves one of the problems of the manufacturer, it creates a problem for the technician. Therefore, before starting to work on any electronic or electrical equipment always ensure that the equipment and any test equipment you are using are properly grounded and that the rubber mat you are standing on is in good condition. As long as you follow these simple rules, you should be able to avoid the possibility of becoming an electrical conductor.

Testing

There are two widely used checks in testing electronic equipment: the visual check and signal tracing.

***Visual Chec*k**. The importance of this check should not be underestimated because many technicians find defects right away simply by looking for them. A visual check does not take long; in fact you should be able to see the problem in a few minutes if it is the kind of problem that can be seen. You should learn the following procedure. You will find yourself using it quite often, as it is good not only for power supplies but also for any other type of electronic equipment you may be troubleshooting.

Before you plug in the equipment, look for the following:

Loose Tubes. A tube that is not properly seated in its socket may not be making proper contact with the rest of the circuit. It may very well be the source of the problem. Push the tube completely into place.

Shorts. Any terminal or connection that is close to the chassis or to any other terminal should be examined for the possibility of a short. A short in any part of the power supply can cause considerable damage. Look for and remove any stray drops of solder, bits of wire, nuts, or screws. It sometimes helps to shake the chassis and listen for any telltale rattles. Remember to correct any problem that may cause a short circuit. If it is not causing trouble now, it may cause problems in the future.

Discolored or Leaking Transformer. This is a sure sign of a short somewhere. Locate it. If the equipment has a fuse, find out why the fuse did not blow: too large a size may have been installed, or there may be a short across the fuse holder.

Loose, Broken, or Corroded Connections. Any connection that is not in good condition is a trouble spot. If it is not causing trouble presently, it will probably cause problems in the future. Fix it.

Damaged Resistors or Capacitors. A resistor that is discolored or charred has been subjected to an overload. An electrolytic capacitor will show a whitish deposit at the seal around the terminals. Check for a short whenever you notice a damaged resistor or capacitor. If there is no short, the trouble may be that the power supply has been overloaded in some way. Make a note to replace the part after signal tracing. It is not worth risking a new part until the trouble has been located.

Plug in the power supply and look for:

Smoking Parts. If any part smokes or if you hear any boiling or sputtering sounds, pull the plug immediately. There is a short circuit somewhere that you have missed in your first inspection. Use an ohmmeter to check the part once again; begin in the neighborhood of the smoking part.

Cold Tubes. After allowing about two minutes for warm-up, touch all the tubes on the equipment. If a tube is cold, it is either burned out or there is a break in the heater connections and the tube is not receiving proper heater voltage. Remove the tube and connect an ohmmeter across the heater terminals to see if the filament is open (reads almost infinite resistance). If the filament reads open, it is burned out. Replace it with a good tube. If the filament reads a low resistance, this indicates that the filament is all right, so use an ac voltmeter to find the break between the filament and the output of the transformer.

Sparking. Tap or shake the chassis. If you see or hear sparking, you have located a loose connection or a short. Check and repair.

If you locate and repair any of the defects listed above, make a note of what you find and what you do to correct it. It is quite probable you have found the trouble. However, a good technician takes nothing for granted. You must prove to yourself that the equipment is operating properly and that no other troubles exist.

If you find none of the defects listed under the visual check, go ahead with the signal tracing procedure. The trouble is probably of such a nature that it cannot be seen directly with your eye: it must be seen through the eye of the oscilloscope.

Signal Tracing. Tracing the ac signal through the equipment is the most rapid method of locating a problem that cannot be found by a visual check, and it also serves as a check on any repairs you may have made. The idea is to trace the ac voltage from the transformer, to see it change to pulsating dc at the rectifier tube filament, and then to see the pulsations smoothed out by the filter. The point where the signal stops or becomes distorted is the place to look for the trouble.

Before you begin signal tracing, it is a good idea to measure the dc voltage. The dc output voltage should be in the neighborhood of 340 volts. If there is no dc output voltage, look for an open or a short in your signal tracing. If there is a low dc voltage, look for a defective part and keep your eyes open for the place where the signal becomes distorted.

Signal tracing is done by observing the waveform at the input and output of each part of a circuit. It is the method used to localize trouble in a circuit.

Let's review what each part of a good power supply does to the signal, as shown in figure 3-50. The ac voltage is brought in from the power line by means of the line cord. This voltage is connected to the primary of the transformer through the on-off switch (S1). At the secondary winding of the transformer (points 1 and 2), the scope shows a picture of the stepped-up voltage developed across each half of the secondary winding--the picture is that of a complete sine wave. Each of the two stepped-up voltages is connected between ground and one of the two plates of the rectifier tube. At the two rectifier plates (points 4 and 5) there is still no change in the shape of the stepped-up voltage--the scope picture still shows a complete sine wave.

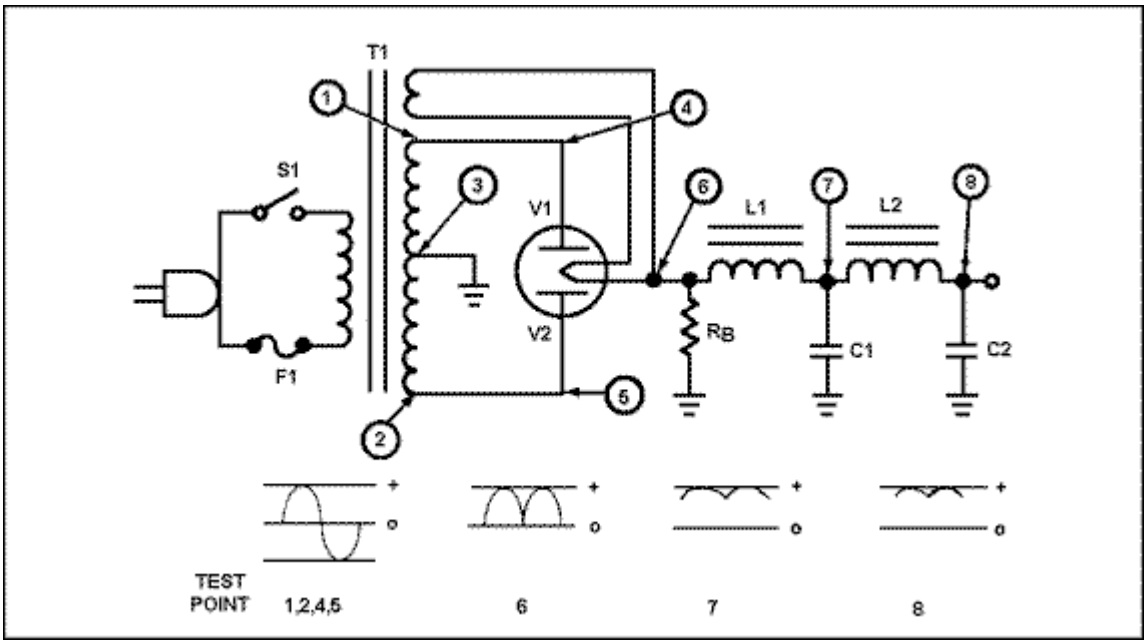

Figure 3-50. Complete Power Supply (Without regulator).

However, when you look at the scope pattern for point 6 (the voltage at the rectifier heater), you see the wave shape for pulsating direct current. This pulsating dc is fed through the first choke (L1) and filter capacitor (C1), which remove a large part of the ripple or "hum," as shown by the waveform for point 7. Finally the dc voltage is fed through the second choke (L2) and filter capacitor (C2), which remove nearly all of the remaining ripple. See the waveform for point 8, which shows almost no visible ripple. You now have almost pure dc. No matter what power supplies you may encounter in the future, they all do the same thing--they change ac voltage into dc voltage.

Component Problems

The following paragraphs give an indication of trouble that occurs with many different electronic circuit components.

Tube Troubles. The symptoms of tube trouble will vary with every type of circuit and each type of tube. However, the problems that can develop with a tube are common to every tube. Here are the five possible tube troubles that can occur. The filament, after long service, may be unable to emit as many electrons as are required for proper operation. The filament may burn out. A tube element--the plate, for instance--may break its connection with the tube base pin. Two elements, such as filament and plate, may short together. The tube may become gassy.

The symptoms you will come across in signal tracing will be many and varied. You will need to combine your knowhow of the circuit and your knowledge of these five possible tube troubles to determine if the tube could in some way be causing the symptoms. If the tube is suspected of causing trouble, try another tube in its place or check it on a tube tester. The final check of whether or not the old tube was bad is whether or not the equipment works properly when a good tube is put in its place. Therefore, putting in a good tube and then trying out the equipment is the best check.

Transformer and Choke Troubles. The transformer and choke are quite similar in construction. Therefore, it is no coincidence that the basic troubles that they can develop are the same. A winding can open (view 1, figure 3-51). Two or more turns of one winding can short together (view 2, figure 3-51). A winding can short to the casing that is usually grounded (view 3, figure 3-51). Two windings can short together (only possible in transformers) (view 4, figure 3-51).

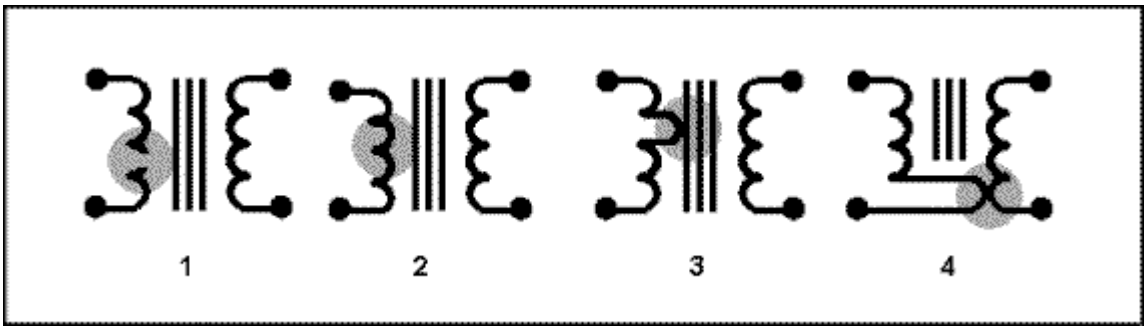

Figure 3-51. Transformer and Choke Troubles.

As with the tube, the symptoms of these troubles will vary with the type of circuit. However, when you have decided that one of these four possible troubles could be causing the symptoms, there are definite steps to take. If you surmise that there is an open winding or windings shorted together or to ground, an ohmmeter continuity check will locate the trouble. You may not be able to detect a difference in winding resistance. Therefore, you need to connect a good transformer in the place of the old one and see if the symptoms are eliminated; but keep in mind that transformers are difficult to replace. Make absolutely sure that the trouble is not elsewhere in the circuit before changing the transformer. Occasionally, the shorts will appear only when the operating voltages are applied to the transformer. In this case you might find the trouble with a megger--an instrument that applies a high voltage as it reads resistance.

Capacitor and Resistor Troubles. Only two things can happen to a capacitor: it may open up, removing the capacitor completely from the circuit (view 1, figure 3-52); or it may develop an internal short circuit. The latter means that the capacitor begins to pass current as though it were a resistor or a direct short (view 2, figure 3-52).

Check a capacitor suspected of being open by disconnecting it from the circuit and checking it with a capacitor analyzer. Check a capacitor suspected of being leaky with an ohmmeter; if it reads less than 500 kilohms, it is probably bad. However, capacitor troubles are difficult to find since they may appear intermittently or only under operating voltages. Therefore, the best check for a faulty capacitor is to replace it with one known to be good. If this restores proper operation, the fault is in the capacitor.

Resistor troubles consist of the following: a resistor can open up (view 1, figure 3-53); a resistor can increase in value (view 2, figure 3-53); and a resistor can decrease in value (view 3, figure 3-53).

To check possible resistor troubles, use an ohmmeter after making sure no parallel circuit is connected across the resistor to be measured. When a parallel circuit is connected across the resistor or when in doubt, disconnect one end of the resistor before measuring it. The ohmmeter check will usually be adequate. However, never forget that occasionally intermittent troubles may develop in resistors as well as in any other electronic parts. The final proof that a resistor is bad is when it is replaced with another resistor, and the equipment operates satisfactorily.

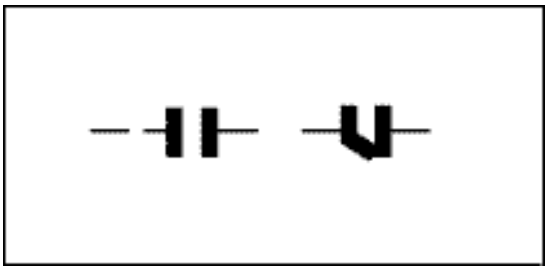

Figure 3-52. Capacitor Troubles

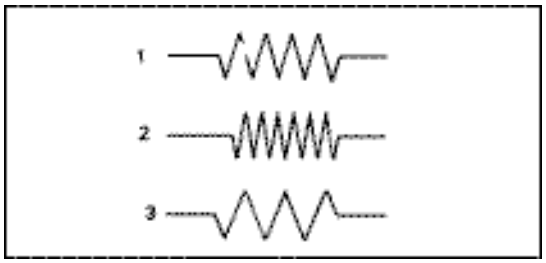

Figure 3-53. Resistor Troubles.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What is the purpose of a regulator?

   a. It maintains a constant voltage to the load.
   b. It maintains a constant current to the load.
   c. It maintains a constant resistance to the load.
   d. It helps the filter.

2. What is the purpose of the transformer in a power supply?

   a. It rectifies ac.
   b. It filters ac.
   c. It isolates ac line voltage from the load.
   d. It acts as a regulator to the load.

3. What is the ripple frequency of a half-wave rectifier with an input frequency of 60 Hz ac?

   a. 60 Hz.
   b. 120 Hz.
   c. 150 Hz.
   d. 180 Hz.

4. What is the equation for determining the average voltage in a half-wave rectifier?

   a. $E_{ave} = .637 \times E_{max}$.
   b. $E_{ave} = .637 \times E_{min}$.
   c. $E_{ave} = .318 \times E_{max}$.
   d. $E_{ave} = .318 \times E_{min}$.

5. For a diode to act as a half-wave rectifier, how should it be connected to the load?

   a. Parallel.
   b. Series.
   c. Series parallel.
   d. It doesn't matter.

6. What components are used in a full-wave rectifier?

   a. A center-tapped transformer and two diodes.
   b. A center-tapped transformer and one diode.
   c. An untapped transformer and two diodes.
   d. An untapped transformer and one diode.

7. What is the ripple frequency of a full-wave rectifier with an input frequency of 100 Hz?

   a. 100 Hz.
   b. 200 Hz.
   c. 300 Hz.
   d. 400 Hz.

8. What is the equation for determining the average voltage in a full-wave rectifier?

   a. $E_{ave} = .318 \times E_{max}$.
   b. $E_{ave} = .637 \times E_{max}$.
   c. $E_{ave} = 1.414 \times E_{max}$.
   d. $E_{ave} = 1.414 \times E_{min}$.

9. What is the advantage of using a bridge rectifier over the conventional full-wave rectifier?

   a. The output ripple frequency is higher.
   b. The output impedance is higher.
   c. The output current is higher.
   d. The output voltage is higher.

10. What unit of measurement is used for capacitive reactance (X_C)?

    a. Volts.
    b. Amperes.
    c. Ohms.
    d. Mhos.

11. What is the formula for capacitive reactance?

    a. $Xc \frac{1}{fC}$.
    b. $Xc = 2\pi fC$.
    c. $Xc = \frac{1}{2\pi fC}$.
    d. $Xc - 2\pi fC$.

12. If the value of a capacitor is increased, how will X_C be affected?

    a. It will remain the same.
    b. It will increase.
    c. It will decrease.
    d. It will increase providing frequency doesn't change.

13. If the value of an inductor is increased, how will X_L (inductive reactance) be affected?

    a. It will remain the same.
    b. It will increase.
    c. It will decrease.
    d. It depends on the frequency.

14. What is the most basic type of filter?

    a. Capacitor filter.
    b. LC choke input filter.
    c. LC input filter.
    d. RC capacitor input filter.

15. How does a filter circuit affect the average output voltage?

    a. It doesn't change.
    b. It decreases.
    c. It increases.
    d. It depends on the frequency.

16. What determines the rate of discharge of the capacitor in a filter circuit?

    a. The value of the capacitor.
    b. The value of the load resistor.
    c. The value of the load resistor and the load resistance.
    d. The type of rectifier used.

17. Where is the LC choke input filter primarily used?

    a. Where good voltage regulation is not important.
    b. Where the output current is relatively high.
    c. Where load conditions are steady.
    d. Where filtering is not a consideration.

18. What is the function of the inductor in an LC choke input filter?

a. To aid any change in voltage.
b. To aid any change in current.
c. To oppose any change in voltage.
d. To oppose any change in current.

19. When would you use an RC capacitor input filter?

a. When voltage regulation is necessary.
b. When the output current is relatively high.
c. When the load current varies.
d. When the load current is small.

20. A no-output condition in an RC capacitor input filter would indicate failure of what component or components?

a. An open filter resistor and an open filter capacitor.
b. An open filter capacitor.
c. A shorted filter capacitor or an open filter resistor.
d. A shorted filter resistor.

21. What is the ideal percent of regulation for a voltage regulator?

a. 0 percent.
b. 50 percent.
c. 75 percent.
d. 100 percent.

22. If a power supply produces 20 volts with no load and 16 volts under full load, what is the percent of regulation?

a. 10 percent.
b. 25 percent.
c. 50 percent.
d. 70 percent.

23. What is the maximum current that a VR75-40 tube may be allowed to carry and still maintain regulation?

a. 40 microamps.
b. 40 milliamps.
c. 40 amps.
d. 75 micro amps.

24. When connecting a VR75-30 and a VR105-40 in series, what are the regulating voltage and maximum current?

a. 180 volts and 70 milliamps.
b. 30 volts and 10 milliamps.
c. 75 volts and 30 milliamps.
d. 180 volts and 30 milliamps.

25. How can the current handling capacity of a voltage regulator be increased?

a. By connecting two VR tubes in series.
b. By connecting two VR tubes in parallel.
c. By connecting three VR tubes in series parallel.
d. By using an electron tube voltage regulator.

26. To regulate the current in a filament supply, what type of regulator should be used?

a. An amperite regulator.
b. An electron tube regulator.
c. A series connected VR tube regulator.
d. A parallel connected VR tube regulator.

27. What is the first thing to be done when troubleshooting a power supply?

a. Turn the power on.
b. Perform voltage checks.
c. Perform a visual inspection.
d. Make waveform checks.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 4
FUNDAMENTALS OF AMPLIFIERS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to describe the fundamentals of amplifiers and their purpose, function, and use.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 2, 3, 5, 6, and 7.

CLASSIFICATION OF AMPLIFIERS

An electrical signal may be amplified, or increased, by electronic means. The vacuum tube amplifier is such a means. Radio, radar, television, telephone, and other electronic devices employ amplifiers to raise the strength of extremely small signals so that they may be seen or heard. The amplifier may consist of a single stage (one vacuum tube and its associated circuits) or several stages.

Since there are so many different amplifier circuits, they are classified according to groups having common characteristics. They may be grouped according to use, coupling between stages, operating conditions, or frequency range.

Use

Since amplifiers may be used to amplify either voltage or current, they may be classified as voltage or power amplifiers. A voltage amplifier is designed to produce a large voltage increase of the input signal. A power amplifier, however, is designed to furnish a large amount of power (current) to a loudspeaker or other power-consuming device.

Coupling Between Stages

The coupling between stages of amplifications may also be used to classify amplifiers. There are four main groups: direct-coupled amplifiers, resistance-capacitance (RC)-coupled amplifiers, impedance-coupled amplifiers, and transformer-coupled amplifiers.

Direct-coupled Amplifiers. Figure 4-1 shows a direct-coupled amplifier consisting of two stages. A dc voltage is applied directly to the grid of the first stage. The plate output of this first stage is then connected directly to the grid of the second stage. The bias and plate supply voltage (B+) for each succeeding stage must be greater than that of the preceding one. Direct-coupled amplifiers are used in vacuum tube voltmeters and electronic voltage regulators where small dc voltage changes must be amplified.

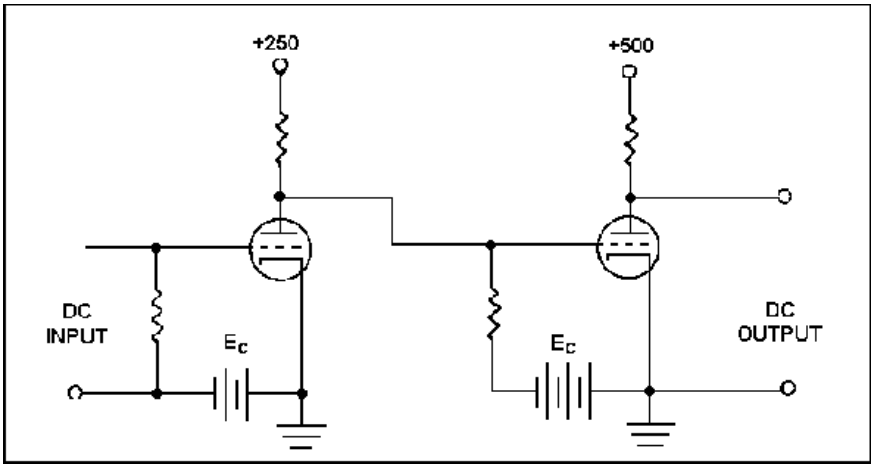

Figure 4-1. Direct-coupled Amplifier.

Resistance-capacitance (RC)-coupled Amplifiers. Figure 4-2 illustrates the most widely used method for coupling between audio stages. The bias for each stage is furnished by cathode voltage. The coupling capacitor, Cc, provides an ac path from the plate of the first stage to the grid of the following stage but blocks any dc voltage. The load resistor, RL, has a large value so that a large voltage change can be coupled to the grid of the next stage. When a signal is applied to the first stage (figure 4-2), voltage variations occur across RL. These voltage variations are then coupled through the RC circuits, Cc and Rg, to the grid of the second tube. The coupling capacitor, therefore, performs the double function of providing a low-impedance ac path and of blocking dc plate voltage from the grid of the second tube.

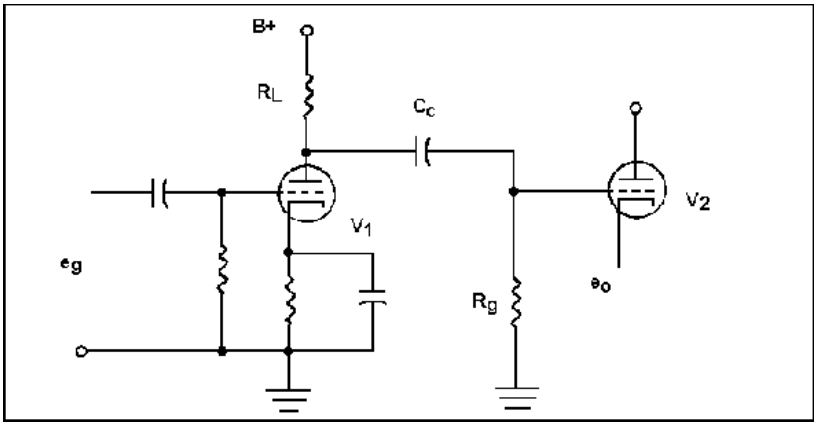

Figure 4-2. RC-coupled Amplifier.

Impedance-coupled Amplifiers. Figure 4-3 shows how an impedance-coupled circuit differs from an RC-coupled circuit. Plate-load resistor RL is replaced by inductor L. The inductance makes possible a greater gain for a given band of frequencies by presenting a low impedance for dc and increasing as the signal frequency increases. Prior to an applied signal, the dc plate voltage is higher if the plate load is an inductance rather than a resistance. However, for a given band of high frequencies, the impedance of L (figure 4-3) becomes greater than that of RL in the RC-coupled amplifier. Therefore, a greater variation occurs across the inductance at the higher frequencies, and a greater gain results.

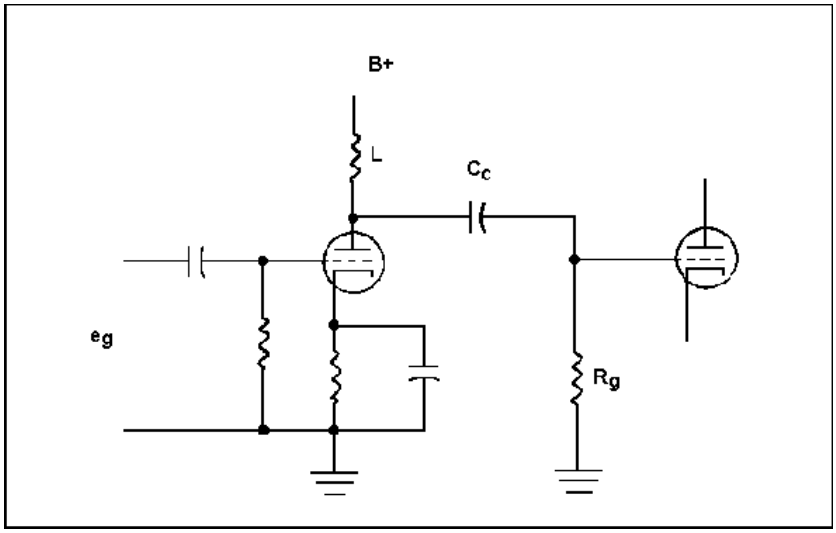

Figure 4-3. Impedance-coupled Amplifier.

Transformer-coupled Amplifiers. Figure 4-4 illustrates another type of coupling often used to couple audio frequencies - the untuned transformer. Because of the step-up property of the transformer, greater gain can be obtained with transformer coupling than with RC or impedance coupling. This greater gain, however, is obtained at the expense of narrowing the amplified bandwidth. Also, note that the transformer performs the double function of coupling ac variations and blocking the dc plate voltage from the grid of the next stage.

The tuned transformer is usually used to couple radio-frequency amplifier stages. Capacitors (shown as dotted lines in figure 4-4) are placed parallel to the transformer primary and secondary, forming two parallel-tuned circuits. Greater gain and narrower bandwidth result from tuned transformer coupling if the merit factor (Q) of the tuned circuits is high.

Operating Conditions

Some amplifiers conduct (operate) during the full 360ø of the signal cycle, while others conduct during only part of the cycle. Classes of operation are related to the percentage of the time during which the amplifier conducts.

For example, class A amplifiers conduct during 360ø (100 percent) of the signal cycle, while class AB amplifiers conduct during more than 180ø (50 percent) but less than 360ø of the input cycle. Class B amplifiers, however, conduct for about 180° of the input cycle, while class C amplifiers conduct for considerably less than 180°.

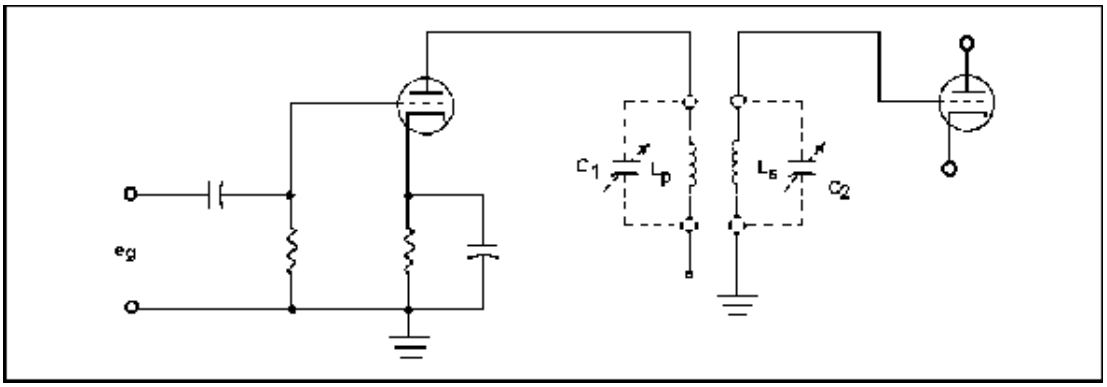

Figure 4-4. Transformer Coupling.

Class A Amplifiers. A class A amplifier is one in which the grid bias and alternating signal voltage are chosen so that plate current flows during the entire cycle. Class A amplifiers are biased to operate on the linear portion of the dynamic curve (figure 4-5). For example, if a 4-volt peak-to-peak signal is applied to the grid of the tube shown in figure 4-5, an amplified output plate voltage is obtained. The load line for this circuit (fig 4-6) illustrates the upper and lower limits of the output voltage. The operating point of this tube (figure 4-5), with no input signal, is the intersection of the load line with the 6-volt (negative) bias line (figure 4-6). As the input signal goes through a cycle, grid voltage varies from -6 volts to -4 volts, back to -6 volts, down to -8 volts, and back to -6 volts. The output plate signal then varies from the operating point of 175 volts, down to 145 volts, and up to 205 volts (figure 4-6). Since the output plate voltage varies 60 volts peak to peak, while the input grid signal is only 4 volts peak to peak, the stage has amplified the input signal by a factor of 15. Note that the output signal varies the same below as above the operating point (figure 4-6). Therefore, it is a faithful reproduction of the input signal and practically no distortion is introduced.

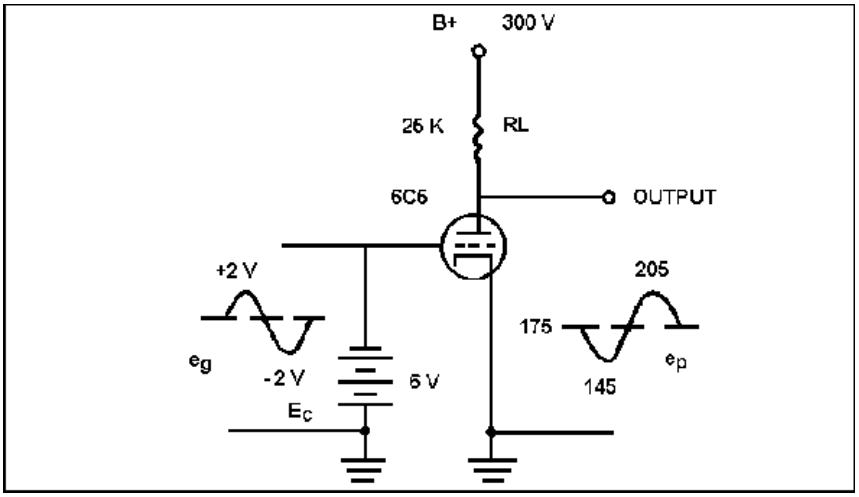

Figure 4-5. Class A Amplification.

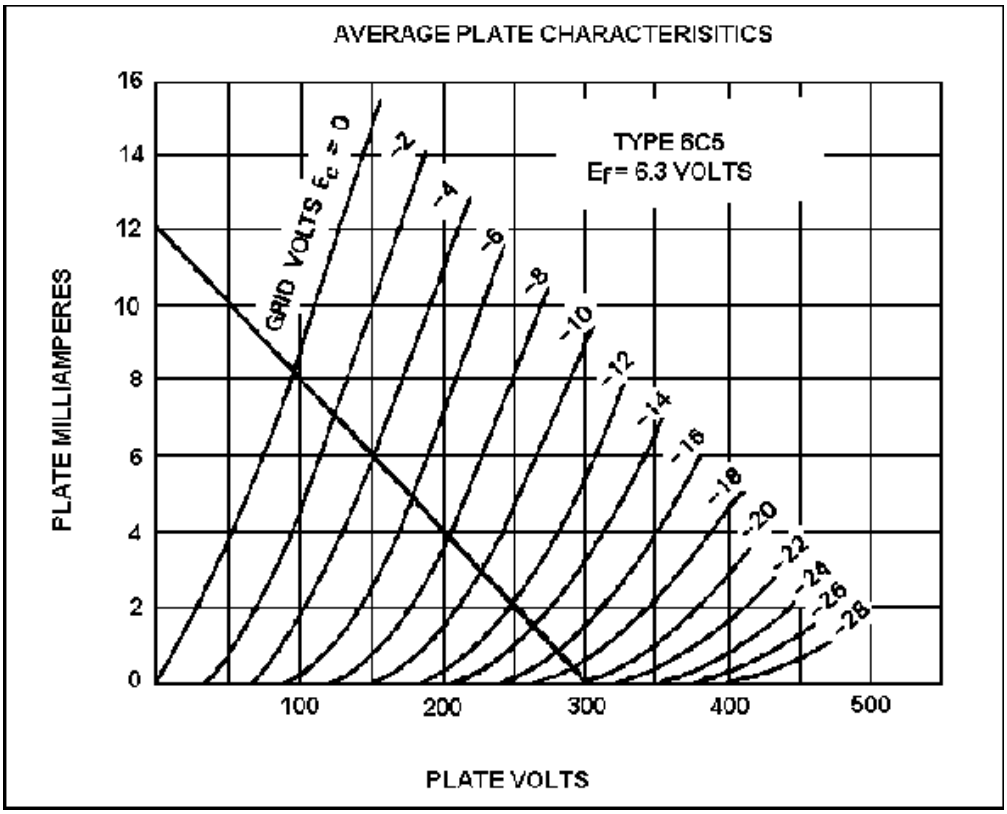

Figure 4-6. Load Line for Class A Amplifier.

Class A amplifiers are mainly used to amplify AF and RF signals in radio, radar, and sound systems. They are, however, noted for their low efficiency, that is, the ratio of power output to power input is low. Theoretically, a class A amplifier has a maximum efficiency of approximately 50 percent, although most practical class A circuits are only about 20-percent efficient.

Class B Ampliliers. A class B amplifier is one in which the grid bias is very close to cutoff (no plate current flows with no input signal). Figure 4-7 shows that plate current (Ip) flows only during the positive half-cycle of the input voltage. During the negative half-cycle, the grid is driven back below the cutoff point of the tube and no current flows.

The efficiency of a class B amplifier is high and the current consumption less as compared to a class A amplifier. Power loss in class B amplifiers is low for two reasons. First, plate current does not flow with no signal applied to the grid; thus, very little power is wasted during non conducting periods.

Second, plate current flows only during the positive half-cycle of the input signal. This means that the average current flow is only 32 percent of the peak current in this stage.

Class B amplifiers are mainly used as power amplifiers. As power amplifiers, their output power is proportional to the square of the grid excitation voltage. The output amplitude distortion of a class B amplifier, operating with the proper load resistance, depends upon the operating point and the departure of the characteristic curve from straight lines. The output shown in figure 4-7 is quite different from that of the distortionless full cycle reproduction of a class A amplifier: one half-cycle is missing. The missing half-cycle is supplied by one of two methods: by an additional class B amplifier or by the flywheel action of a resonant circuit.

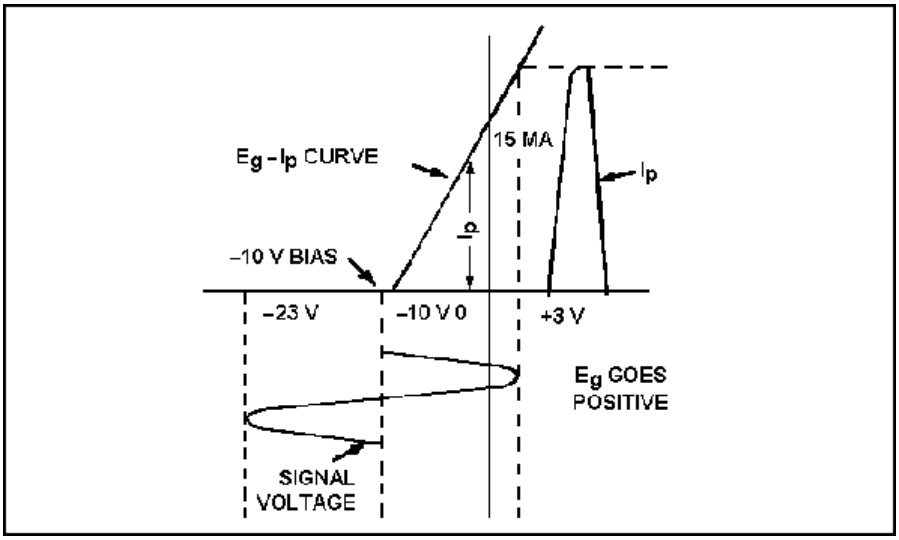

Figure 4-7. Class B Amplification.

Push-pull Class B Amplifier. A push-pull class B amplifier is composed of two tubes connected so as to develop in the output both halves of the input cycle. Figure 4-8 shows that one tube conducts during the first half-cycle of the ac input, and the other tube conducts during the last half-cycle. Since plate current flows during one half-cycle in one tube and during the next half-cycle in the other, the plate-current waveforms are combined in the load circuit. The load circuit of the push-pull amplifier is the center-tapped primary of the output transformer. During one half-cycle, one tube produces a voltage across the transformer winding. During the next half-cycle, the other tube produces a voltage of opposite polarity across the winding. Since the plate currents of the two tubes flow in opposite directions through their respective halves of the transformer primary winding, the voltage across the primary, combines in the secondary to produce a reasonably undistorted output of the input ac voltage.

Single-tube Class B Amplifier. A single-tube class B amplifier can be successfully used in an RF amplifier stage if a parallel-tuned circuit is employed as a plate load. Because of its ability to store power, the parallel-tuned circuit is sometimes called a tank circuit. When it is used as the plate load of a single-ended class B amplifier (figure 4-9), the tank capacitor is charged by the plate current flow during positive half-cycles of the input. Since no current flows through the load on the negative input alternations (half-cycles), the capacitor discharges through the inductor during this period and supplies the missing half-cycles in the output. This oscillatory (flywheel) effect of the tank circuit occurs only when the tank circuit resonant frequency is equal to the input signal frequency.

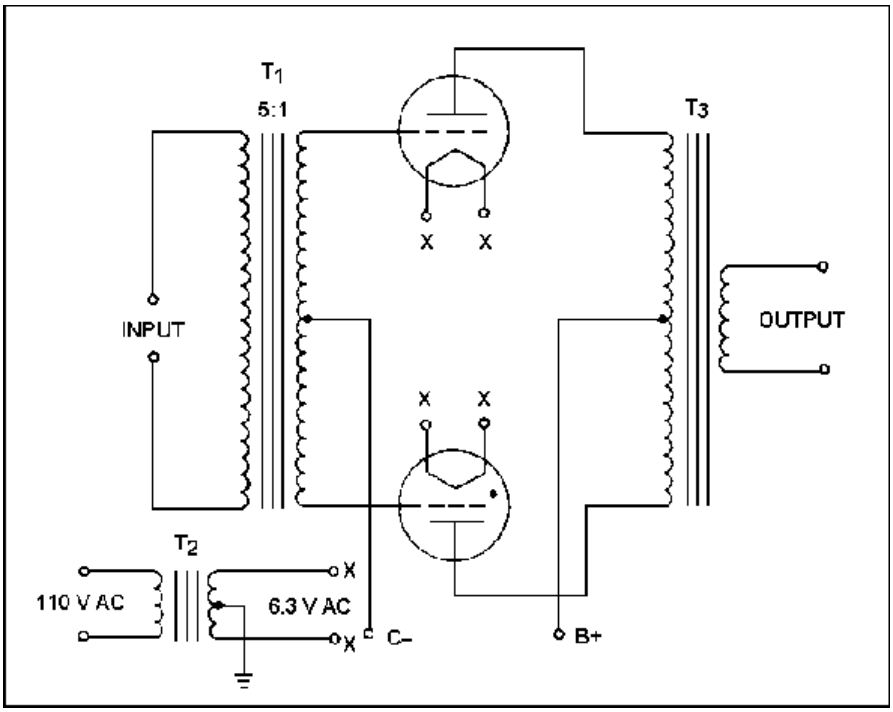

Figure 4-8. Push-pull Amplifier.

The maximum amount of useful power available from a single power tube is limited by the amplitude distortion caused by the introduction of undesired harmonic frequencies. A harmonic frequency is a multiple of any given frequency. For example, the second harmonic of 1,000 hertz is 2,000 hertz, the third harmonic is 3,000 hertz, and so on. These harmonics are generated by nonlinear, grid voltage-plate current changes in a vacuum tube.

By using a push-pull circuit configuration or a tank circuit, the efficiency of a class B power amplifier can be improved. Although the theoretical maximum efficiency possible is 78.5 percent, most practical applications only attain between 60 and 65 percent.

Class C Amplifiers. A class C amplifier is one in which the grid bias is appreciably greater than the cutoff value of the tube. With no ac input voltage applied to the grid, the plate current is zero. When an input voltage is applied to the grid, plate current flows for appreciably less than one-half of one cycle (figure 4-10).

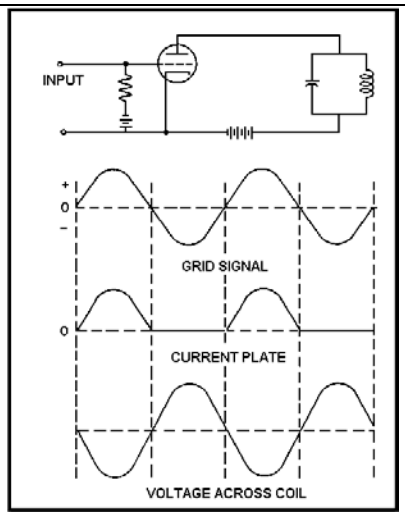

Figure 4-9. Class B Amplifier With Resonant Tank.

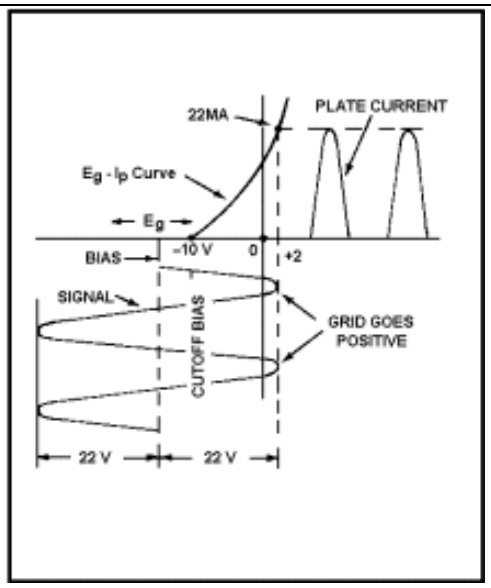

Figure 4-10. Class C Amplification.

Except for grid bias, class C amplifiers operate in the same way as class B amplifiers. Since current flows for only a small part of a cycle, the distortion in class C amplifiers is very great. For example, the grid of a class C amplifier usually swings sufficiently positive to allow saturation-point current flow through the tube. As a result, harmonics are introduced to the output plate wave. These undesired harmonics can be eliminated by adding a tuned tank circuit to the load (figure 4-11). The tuned tank (tuned to the input frequency) offers a high impedance to the input operating frequency with a power factor nearly equal to unity. However, it presents a low impedance to the harmonic frequencies, causing them to be attenuated. The signal frequency is therefore amplified to a much greater extent than are the harmonic frequencies.

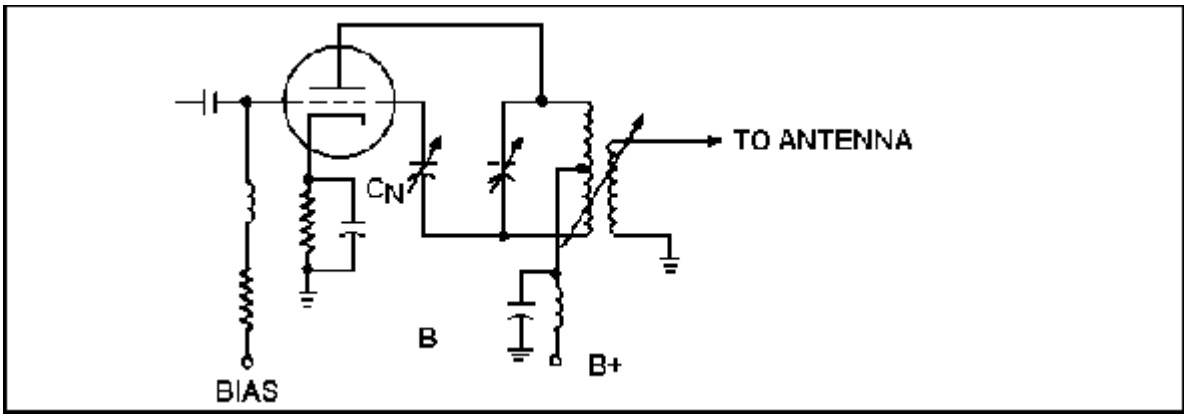

Figure 4-11. Preventing Distortion With a Resonant Tank.

Class C amplifiers are often used in high-frequency equipment where it is necessary to deliver appreciable power. The high efficiency of a class C amplifier--usually between 60 to 80 percent--is due to the fact that the instantaneous plate potential is low, compared to the plate supply voltage, when plate current flows. Therefore, energy is supplied to the plate circuit only when the current causes a voltage drop across the tuned circuit.

Frequency Range

Amplifiers may also be classified according to the band of frequencies in which they are designed to operate. There are four main divisions: direct current amplifiers, audio-frequency amplifiers, video-frequency amplifiers, and radio-frequency amplifiers.

Direct Current Amplifiers. Direct current amplifiers are used to amplify slow or irregular dc changes down to 0 hertz (cycles per second). They are also used to amplify very low frequencies or dc voltages. A simple dc amplifier consists of a single tube with a grid resistor across the input terminals and a load in the plate circuit (figure 4-12). The parallel voltmeter indicates the voltage drop across the load resistor RL. With no dc input, the tube is conducting normally, and the voltage across RL is determined by the current at the operating point. If a positive dc voltage is applied to the grid (Eg), the tube conducts harder and more voltage is dropped across RL If a negative dc voltage is applied to the grid, the tube conducts less, and the voltage decrease is noted on the voltmeter (figure 4-12). Moreover, a small dc voltage change at the grid appears as a larger change across RL.

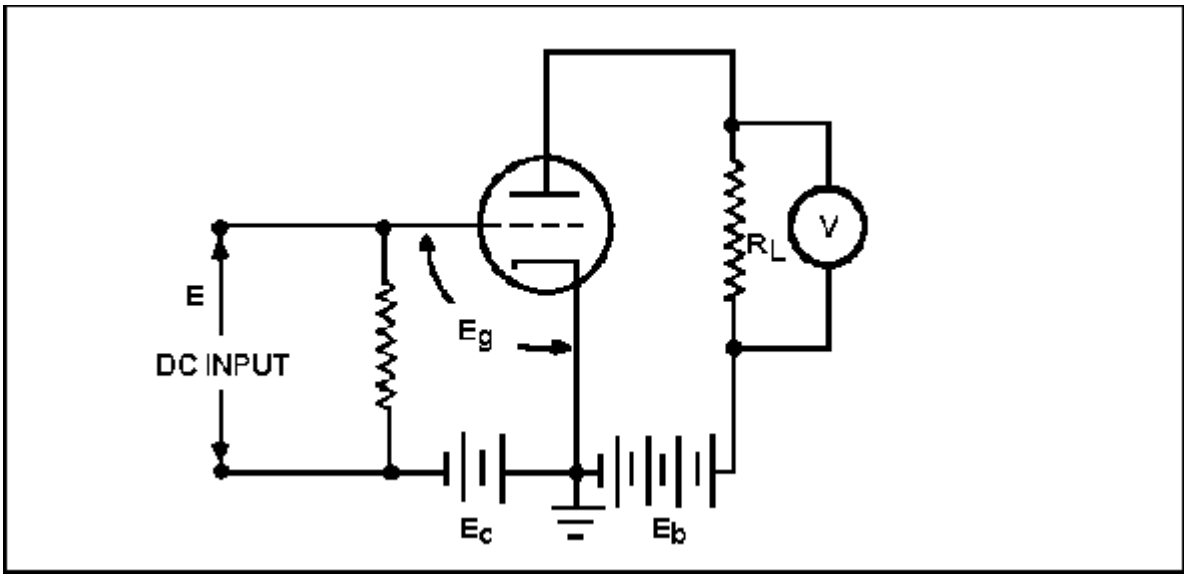

Figure 4-12. Direct Current Amplifier.

The load used in the plate circuit may be some sort of mechanical device, such as a relay or meter, or the output voltage may be used to control the gain of another amplifier. The dc voltage to be amplified must be applied directly to the grid of the amplifier tube. For this reason, only direct coupling can be used in the amplifier input circuit.

One of the most important uses of a dc amplifier is in a dc vacuum tube voltmeter (figure 4-13). The voltage to be measured is applied to the voltage dividers, R1 through R4. The ratio of voltage division can be varied by a volt- age range switch so that several voltage ranges can be measured.

Resistor R5 is used to prevent damage to the meter if an exceptionally high voltage is applied. In the plate circuit, the additional battery and the variable resistor are used to balance the normal circuit plate current. The variable resistor (R6) can be adjusted so that meter M reads zero with no applied input signal. If a dc voltage is applied to the input (figure 4-13), the tube amplifies it and causes current to flow through the meter. Since the meter reading is proportionate to the applied voltage, the amount of voltage can be read on the calibrated meter scale.

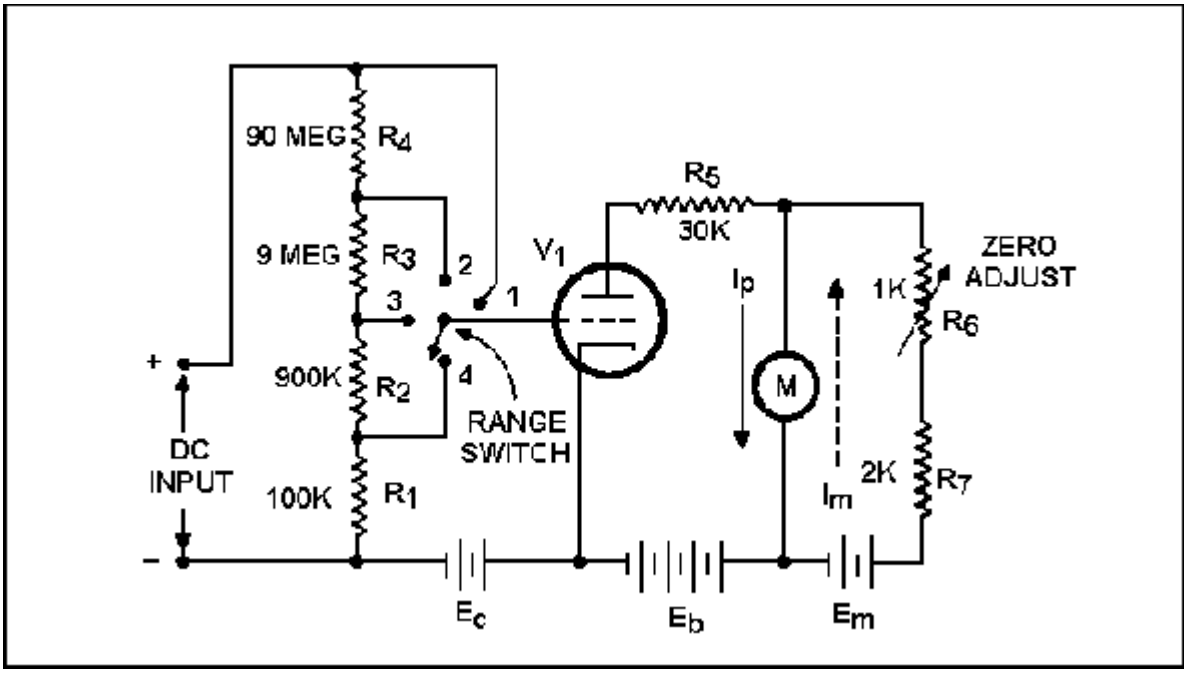

Figure 4-13. Vacuum Tube Voltmeter.

Direct current amplifiers can also be used as voltage regulators where small voltage changes must be amplified for control purposes. Another important application of dc amplifiers is found in the automatic-frequency control (AFC) circuits of many radar sets. In these circuits, a frequency change is converted to a voltage change and then amplified by a dc amplifier. This voltage is then sent as a frequency-correcting signal to the transmitter.

Audio-frequency Amplifiers. Amplifiers designed to operate at frequencies within the audio spectrum (approximately 20 to 20,000 hertz) are called audio-frequency amplifiers. To obtain sufficient gain, it is usually necessary to use more than one stage of audio amplification. In this case the output of the tube is used to control the grid circuit of the second tube, then the amplified output of the second tube is used to control the grid of the following tube, and so on. When two or more amplifiers are connected in this manner, they are said to be connected in cascade.

RC coupling is the most widely used type of coupling in audio circuits, although impedance coupling and transformer coupling are sometimes useful. Figure 4-14 shows a typical RC-coupled audio amplifier. The dotted capacitors are the interelectrode and stray-wire capacitances present in the plate circuit of one tube (Cp) and the grid circuit of the following stage (Cg). Cc and Rg make up the circuits' RC-coupling network.

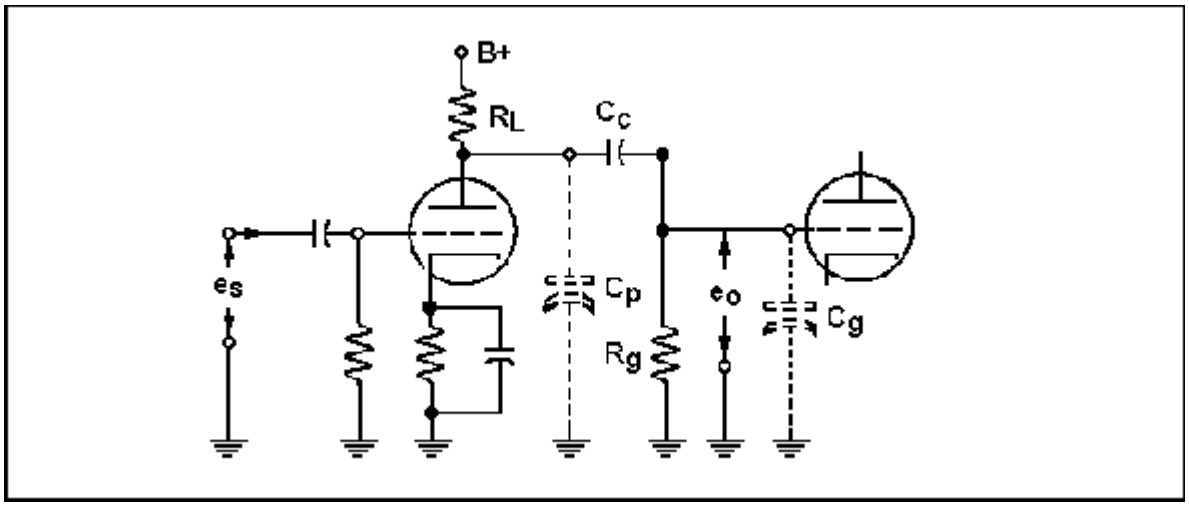

Figure 4-14. RC-coupled Audio Amplifier.

The amplification of an RC-coupled audio amplifier varies with the input signal frequency. A of figure 4-15 shows the amplification variation over a wide range of frequencies. Note that the amplifier gain decreases at the low and high frequencies but remains fairly constant in the middle-frequency range. The low response at the lower frequencies is caused by the high reactance of the coupling capacitor, Cc (figure 4-14). At the high frequencies, the low response is due to the shunting effect of the interelectrode and stray capacitances. Both of these effects, however, are negligible in the middle frequency range. B and C of figure 4-15 show the effects that load resistor RL and coupling capacitor Cc (figure 4-14) have on the frequency response of the audio amplifier.

The bandwidth of an amplifier is determined by the frequencies at which the amplification drops to approximately 70 percent of the maximum value. A of figure 4-15 shows that a line drawn through a voltage amplification of 42 (70 percent of 60) determines the bandwidth. Note that the entire audio-frequency range (20 to 2,000 hertz) is included in the bandwidth of this example.

Video-frequency Amplifiers. Radar and television signals require amplifiers that can amplify a wide band of frequencies. Such amplifiers, having a uniform response over a frequency band extending from the lowest audio frequency to frequencies of several megahertz, are known as video amplifiers. Like audio amplifiers, most video circuits use RC coupling, although the circuit component values are different. The frequency response curve of the RC-coupled audio amplifier (figure 4-15) drops rapidly at low and high frequencies but is fairly uniform over the middle audio-frequency range. The low-frequency response is limited by the value of the coupling capacitor, and the high-frequency response is limited by the interelectrode and stray wire capacitance of the plate and grid circuits. These limiting factors must be overcome in order to widen the amplifier bandpass so that its response is uniform over the wide-frequency range required by a video signal.

Triodes, which have high-interelectrode capacitance, are not suitable for use as video amplifiers. Rather, pentodes, which have very low-interelectrode capacitances, are used. In addition, the pentode has a higher amplification factor than the triode. However, in wiring the circuit, care must be taken to keep the leads short and properly spaced for minimizing the distributed capacitance of the wires.

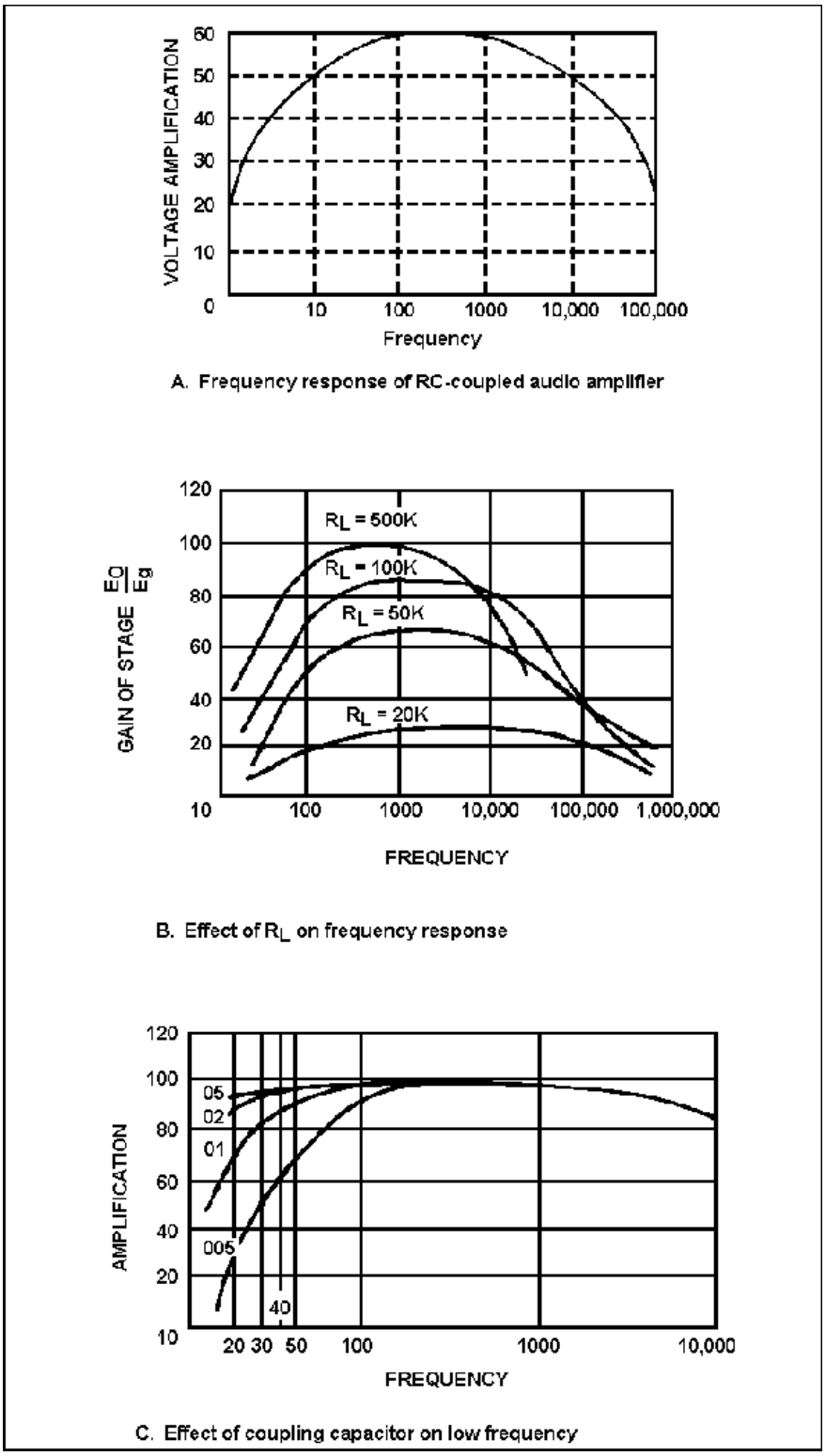

Figure 4-15. Response Curves of an RC-coupled Audio Amplifier.

The value of the load resistor in an RC-coupled amplifier determines, to a great extent, the bandwidth and gain of its amplifier. B in figure 4-15 shows the effect of changing the value of load resistor RL. Note that the highest resistance value causes a high-output voltage in the mid-frequency range and a steep-output voltage drop at the high frequencies. As RL is decreased, although the gain in the mid-frequency range is lower, the response is more uniform over a wider range.

High-frequency amplification is limited by capacitances that shunt the load, while low-frequency amplification is limited by the size of coupling capacitor C_c. To improve their frequency response, video amplifiers employ pentodes to reduce interelectrode capacitances and low-value load resistors to broaden the response. In addition, special devices are often added to improve the low and high-frequency responses.

Low-frequency Compensation. Video amplifiers must be capable of amplifying frequencies at the low end of the frequency band as well as at the high end.C of figure 4-15 shows that low-frequency amplification is improved when a large coupling capacitor (C_c) is used. A large capacitor has less reactance to low frequencies than does a small capacitor and therefore has a smaller voltage drop. Since coupling capacitor C_c and grid resistor Rg (figure 4-16) form a voltage divider in the input circuit, more voltage appears across R_g when C_c has a small reactance and greater amplification results.

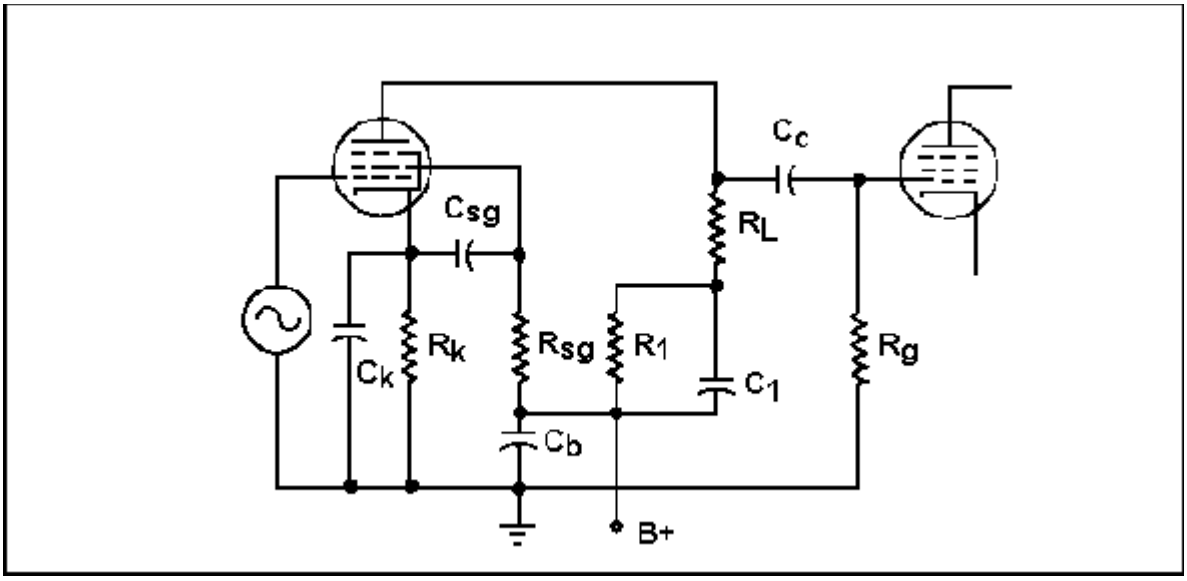

Figure 4-16. Low-frequency Compensation Circuit.

There is a limit, however, to the amount of amplification made possible by increasing the size of C_c. For example, in radar waveshape if C_c is too large, it discharges too slowly for faithful reproduction of the steep trailing edges.

A more satisfactory means of improving low-frequency amplification is to employ a low-frequency compensating circuit. The compensating circuit is composed of a parallel RC circuit connected in series with the load resistor (figure 4-16). Since C_1 is comparatively large, it offers practically no reactance to middle and high frequencies, and therefore, does not affect them. At low frequencies, however, its reactance is high. Since this reactance is parallel to R_1, it produces an impedance that when added to R_L increases the total load impedance. Therefore, since the compensating circuit produces a larger load impedance at low frequencies, the gain of the stage is higher at these frequencies.

High-frequency Compensation. Although amplifier bandwidth is increased by using low-value load resistors, amplification at the high-frequency end is limited by the capacitance (C_s), which shunts the load resistor. High frequency compensating circuits are used in many video amplifiers to offset the effects of the shunt capacitances. As shown in figure 4-17, a low reactance coil (L) may be placed in series with the load resistor (R_L) and in shunt with C_s. At low and middle frequencies, the coil reactance is high and the amplifier gain increases. This gain increase will offset the loss caused by shunting effect C_s (figure 4-17). The value of the coil is usually chosen so that it forms a resonant circuit with the shunt capacitance at a frequency where the gain is low and then increases the gain at this frequency. In this manner, the shunt peaking coil extends the band of frequencies that the video amplifier can uniformly amplify.

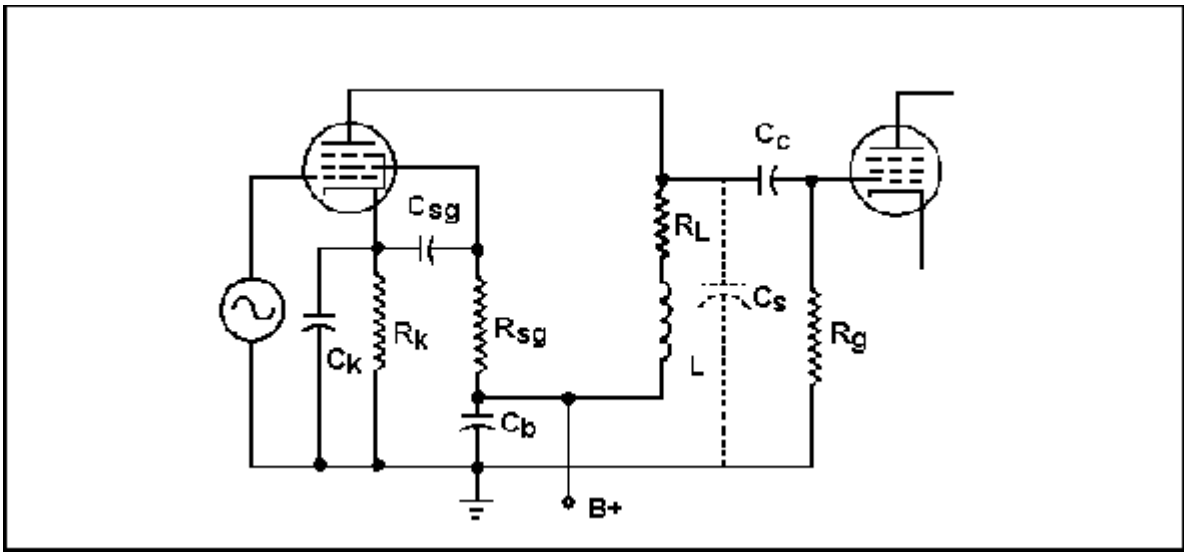

Figure 4-17. Shunt Peaking Coil for High-frequency Compensation.

The series peaking coil is another type of high-frequency compensating circuit. As shown in figure 4-18, a coil L is connected in series with the coupling capacitor C_c. At high frequencies for all practical purposes, inductance L and capacitor C_s form a resonant circuit. The increased current then causes an increased voltage drop across C_s, and a greater voltage is applied to the grid of the following stage.

Figure 4-19 is an RC-coupled video amplifier that incorporates all the compensating devices for extending the bandwidth of a video amplifier. Note that both methods of high-frequency compensation are used to extend the upper range of frequencies that can be amplified.

Radio-frequency Amplifiers. Radio-frequency (RF) amplifiers, mainly used in transmitters and receivers, amplify voltage or power at radio frequencies. With certain limitations they are designed to handle all frequencies above the audio-frequency ranges. One of the most important types of RF amplifiers is the intermediate-frequency (IF) amplifier. Used in super-heterodyne receivers, the IF amplifier differs from the RF amplifier only in use and frequency employed. For example, a typical RF amplifier for a radio receiver might amplify a frequency of 610 kilohertz, while the IF amplifier would be tuned to 455 kilohertz. A radar receiver, on the other hand, might use RF amplifiers at 175 megahertz and IF amplifiers at 30 megahertz.

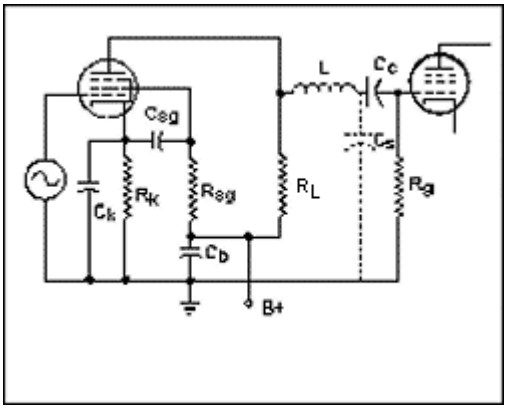

Figure 4-18. Series Peaking Coil for High-frequency Compensation.

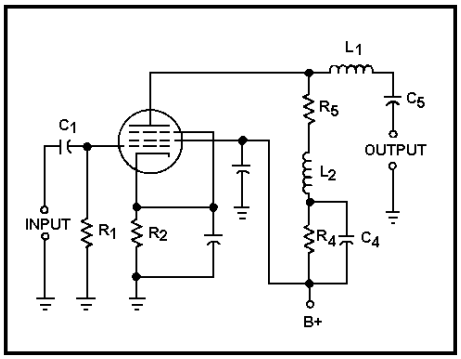

Figure 4-19. RC-coupled Video Amplifier With Compensating Circuits.

RF amplifiers, like audio amplifiers, may operate as classes A, B, or C amplifiers. They differ from audio amplifiers in that tuned resonant circuits are usually used for input and output coupling (figure 4-20). For low-power operation, such as that required in receivers, pentode RF amplifiers provide the highest gain and because of their low grid-to-plate capacity have the least tendency to break into self-oscillation.

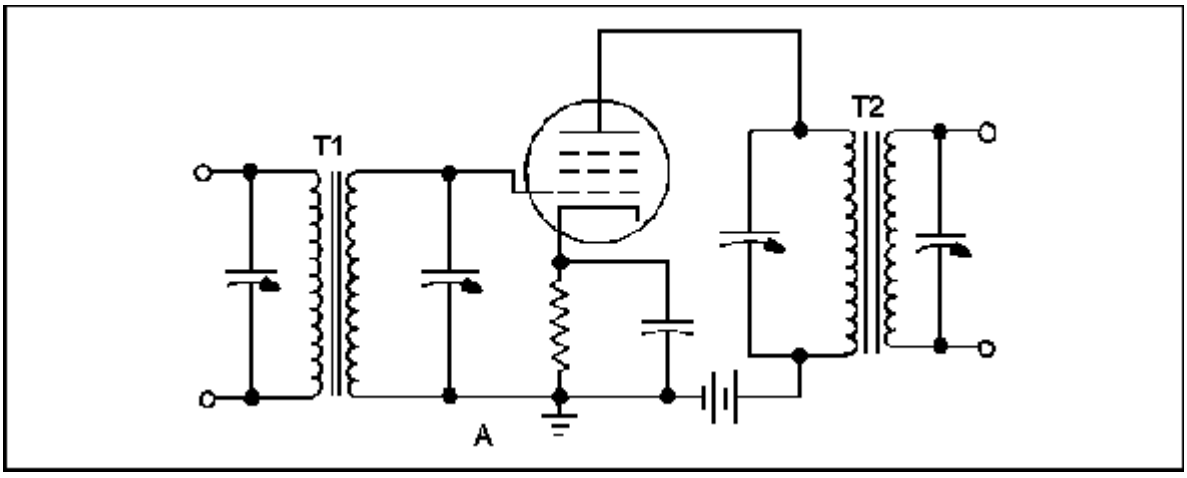

Figure 4-20. RF Amplifier.

The RF amplifier shown in figure 4-20 is actually an IF amplifier since it is designed to amplify only one frequency. Single-frequency amplification occurs because of the parallel resonant circuits at the input and output ends. These parallel circuits discriminate against all frequencies other than resonance by developing maximum voltage only at the resonant frequency. This ability of an amplifier to select one frequency and reject all others is called selectivity. Amplifier selectivity is greatest when high-Q tuned circuits are used.

IF amplifiers used in radar receivers must be of a special design. For example, a pulse-modulated RF signal contains the radio frequency and sidebands for each frequency that makes up the pulse. Therefore, the IF amplifier must have a very wide bandwidth to amplify the entire input pulse. Several devices may be employed to widen the individual IF stage bandwidth, but they will also lower the gain. Radar receivers, therefore, usually employ six or more IF stages to build up the gain to a usable level.

IF amplifiers may either be single-tuned or double-tuned. Figure 4-21 shows that a single-tuned stage has only one tuned circuit between input and output stages, while the double-tuned stage has two. Double-tuned coupling produces greater gain for a given bandwidth, but single tuning is simpler to align and manufacture.

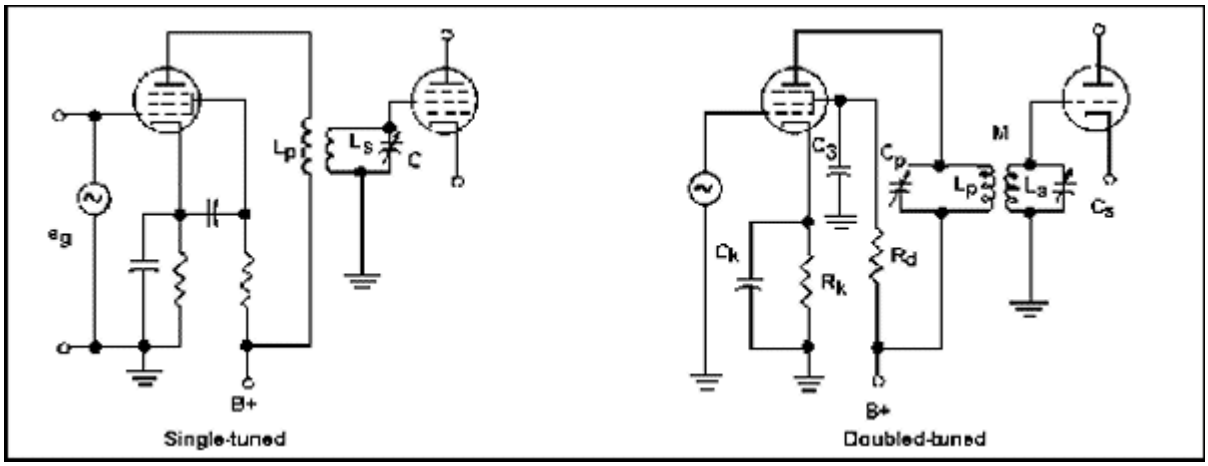

Figure 4-21. Single-tuned and Double-tuned IF Amplifiers.

The IF bandwidth is usually increased by either of two methods: lowering the Q of the tuned circuits or using stagger tuning. The Q can be lowered by resistive loading of the tuned transformer. For example, in figure 4-22, resistors R1 and R2 are connected parallel to their respective coils. The bandwidth can be widened further by decreasing the resistance of R1 and R2, but the gain is considerably decreased. Stagger tuning is accomplished by tuning some IF stages slightly below, some slightly above, and some to the intermediate frequency (figure 4-23). Stagger tuning increases the bandwidth but also lowers the overall gain.

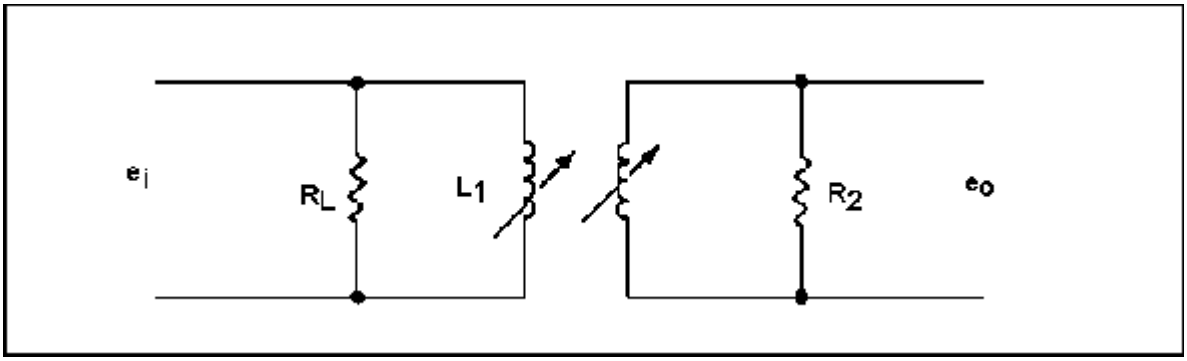

Figure 4-22. Lowering the Q of Tuned Circuits.

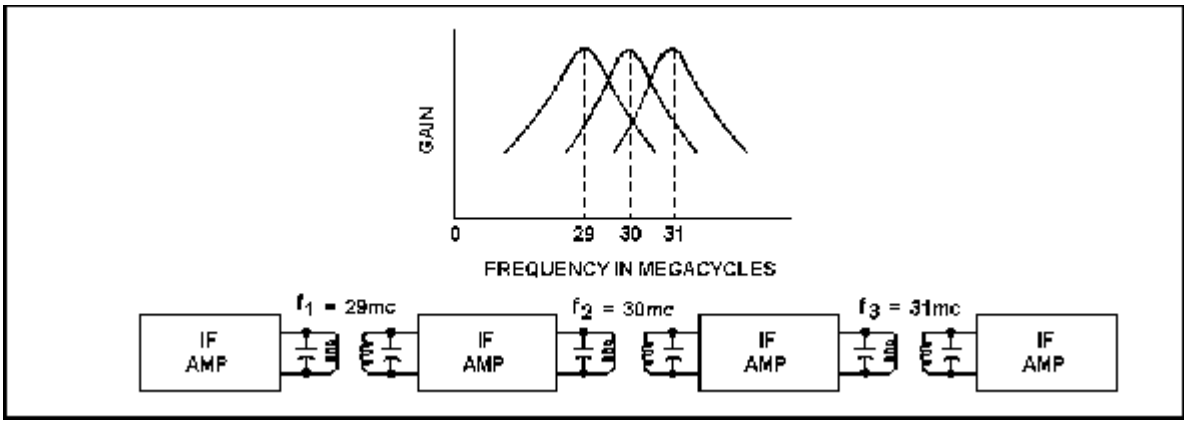

Figure 4-23. Stagger Tuning.

CATHODE FOLLOWER

Maximum transformer power transfer takes place when the source impedance is matched to the load impedance. Although the transformer is limited because of its comparatively poor-frequency response, it is often used as a means of impedance matching. However, where fidelity is of prime importance, such as in radar, a vacuum tube circuit is commonly used to match impedances. Since the problem of impedance matching is usually one of connecting the output of a high-impedance source to a low-impedance device (such as a coaxial cable), the impedance-matching circuit must have a high-impedance input and a low-impedance output. The cathode follower is a circuit that meets these requirements.

The cathode follower is an amplifier in which degenerative feedback occurs because of an unbypassed cathode resistor (figure 4-24). The circuit is essentially an impedance-matching device with a voltage gain less than unity. It does, however, yield a power gain and is therefore classified as a power amplifier. The cathode follower also has an excellent frequency response, often being used as the final video stage in a radar receiver.

Figure 4-24 shows that the cathode follower input (e_i) is applied to the grid of the tube, and the output (e_o) is taken across the cathode resistor. Since the grid resistor (R_g) has a high value and the cathode resistor has a low value, the circuit fulfills the requirement of a high-impedance input and a low-impedance output. As the input voltage goes more positive, plate current increase and the cathode-to-ground voltage (E_{Rk}) goes more positive. If the input voltage goes more negative, however, plate current and the cathode-to-ground decrease. Note that the cathode voltage follows the input signal.

In radar the output from one unit of equipment is often transmitted through a long cable to another unit. Such a cable because of its distributed capacitance, inductance, and resistance presents a much lower impedance than the output impedance of the ordinary amplifier. A cathode follower, however, may be designed to have this low-output impedance and would therefore permit more power transfer than would an ordinary amplifier.

The input impedance of a cathode follower is considered to be high. Since the cathode follower is operated with the grid negative in respect to the cathode, a high-voltage amplitude can be applied between the grid and ground, and no grid current will flow. This can be attributed to the degenerative action of the unbypassed cathode resistor and the high-input impedance to a positive input signal. Moreover, since the cathode follower is a degenerative circuit, very little amplitude distortion is introduced in the output and the input and output signals are always in phase.

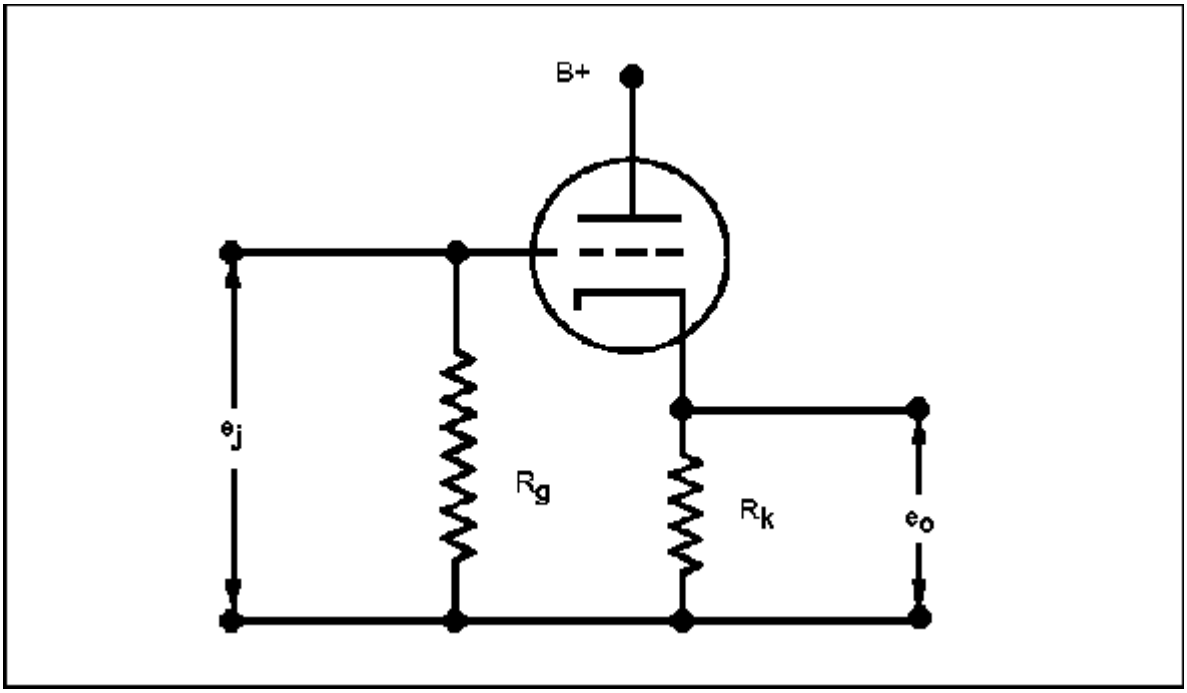

Figure 4-24. Cathode Follower.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1 What is the advantage of using transformer coupling?

a Increased selectivity.
b Increased bandwidth
c Increased bandpass
d Increased gain.

2 What amplifier class has the greatest efficiency?

a A.
b AB.
c B.
d C.

3 What is the primary function of the cathode follower circuit?

a Voltage amplification.
b Impedance matching.
c Current amplification.
d Frequency multiplication.

4 What type of coupling is most widely used in audio amplifiers?

a RC.
b RL.
c Impedance.
d Transformer.

5 What amplifier class is primarily used with audio-frequency systems?

a A.
b AB.
c B.
d C.

6 What amplifier can best be used in a voltage regulator?

a Audio.
b Video.
c Direct current.
d Audio-frequency.

7 Amplifiers are normally classified according to the use, frequency range, and type of what?

a Modulation.
b Coupling.
c Construction.
d Biasing.

8 Why must video amplifier leads be short and properly spaced?

a To decrease frequency drift.
b To minimize radiation losses.
c To decrease resistive absorption.
d To minimize distributed capacitance.

9 What component is used to provide high-frequency compensation in a video amplifier?

a Parallel tank.
b Series peaking capacitor.
c Series peaking inductor.
d Series tank.

10 What type of coupling is most widely used in RF amplifiers?

a Resistive-inductive.
b Resistive-capacitive.
c Untuned transformer.
d Tuned transformer.

11 What type of circuit produces the greatest selectivity in an amplifier?

a High-Q tuned.
b Low-Q tuned.
c High-Q nonresonant.
d Low-Q nonresonant.

12 What amplifier normally maintains the highest selectivity?

a RF.
b AF.
c DC.
d RC.

13 What is a characteristic of the cathode follower circuit?

a High-voltage gain.
b Low-power gain.
c High-input impedance and low-output impedance.
d Low-input impedance and high-output impedance.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 5
OSCILLATORS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to describe the fundamental theory, construction, and operation of oscillators.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 2, 3, 4, 6, and 7.

INTRODUCTION TO SINUSOIDAL OSCILLATORS

An oscillator circuit is one that delivers an ac output voltage, usually having a definite desired waveform and frequency, without the use of an external input signal. The operation of an oscillator circuit depends on a special application of the principles of amplifier circuits.

Application

An important application of oscillators having sinusoidal output waveforms is in the signal generator, a test instrument used in testing amplifiers and other electronic equipment. A signal generator contains one or more oscillator circuits, together with auxiliary circuits, for varying the magnitude and frequency of the output voltage or otherwise contributing to the convenience or precision of the instrument in practical use. The term oscillator is sometimes used to designate the entire signal generator.

Figure 5-1 shows a signal generator. The signal generator supplies the input voltage that enables the amplifier to function. Its output is measured with a voltmeter, an oscilloscope, or other suitable instrument. Signal generators are used to measure the gain, frequency response, and distortion of amplifiers. They are also used to test filter performance, measure frequency, calibrate other oscillators, and make bridge measurements of unknown reactances at specified frequencies.

Basic Principles

Basically, an oscillator is an amplifier that derives its output signal from its own output. This basic principle of oscillator operation is illustrated in B and C of figure 5-2. The amplifier in B has a gain of 10. It produces an output of 10 volts when 1 volt is applied to the input terminals from the generator with the switch in position 1. It is important to note that the input and output voltages of the amplifier have the same polarity (in phase). In C, switch contact 2 has been connected to the load resistor.

Thus, when the amplifier input switch is thrown from position 1 to position 2, the external input voltage, in B, is replaced by the exact duplicate obtained, however, from a tap on the output load resistor of the amplifier. The new input voltage is identical to the original external input signal in both amplitude and phase; therefore, the external input signal is no longer needed, and the amplifier continues to produce an output voltage as long as the feedback path from output to input is not disturbed. Under these conditions the amplifier is said to oscillate.

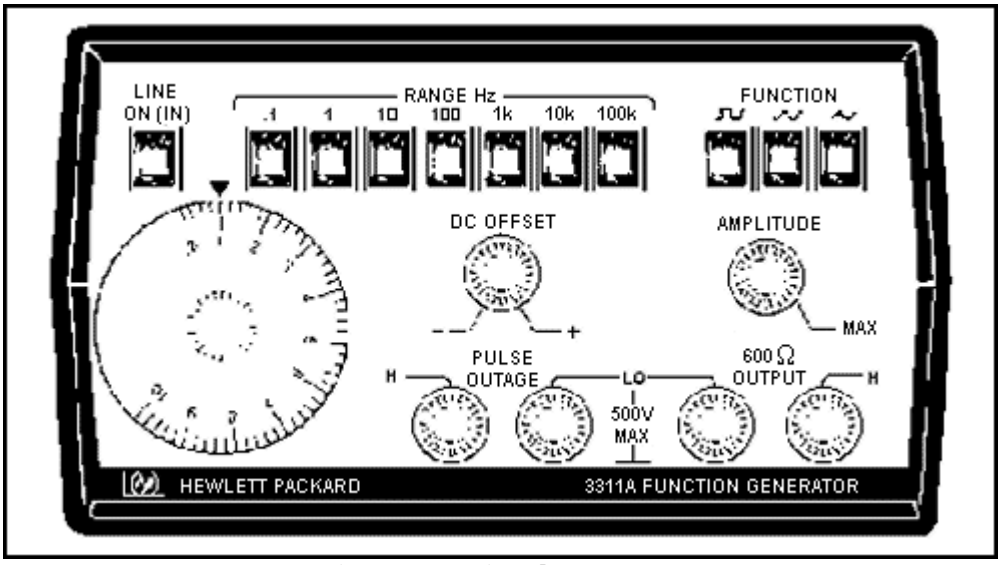

Figure 5-1. Signal Generator.

In practical oscillators, the oscillations are started by variations in plate current as the tube heats up. They build up because of the feedback path and the amplifying action of the circuit. It is not necessary to use an external generator and a switch. These elements are shown merely to illustrate the principle.

The preceding explanation of oscillator operation shows that an amplifier performs as an oscillator provided a portion of its amplified output voltage is fed back with a specific amplitude and phase. These are the two basic operation conditions of many types of oscillators used as signal generators.

In many practical oscillators, the requirements of phase and amplitude are fulfilled by networks of resistors and capacitors that are inserted in the feedback loop of a conventional amplifier. These networks also determine the frequency of the oscillator output. Oscillators of this type are called RC oscillators. Since practical oscillators are used for test purposes, their performance must meet rigorous specifications as to output voltage and frequency.

Requirements

Signal generators are often equipped with attenuators or other circuits by which the amplitude of the output voltage may be varied at will; but, once the control is set, the output must remain constant over a wide range of frequencies and for long periods of time at any one setting.

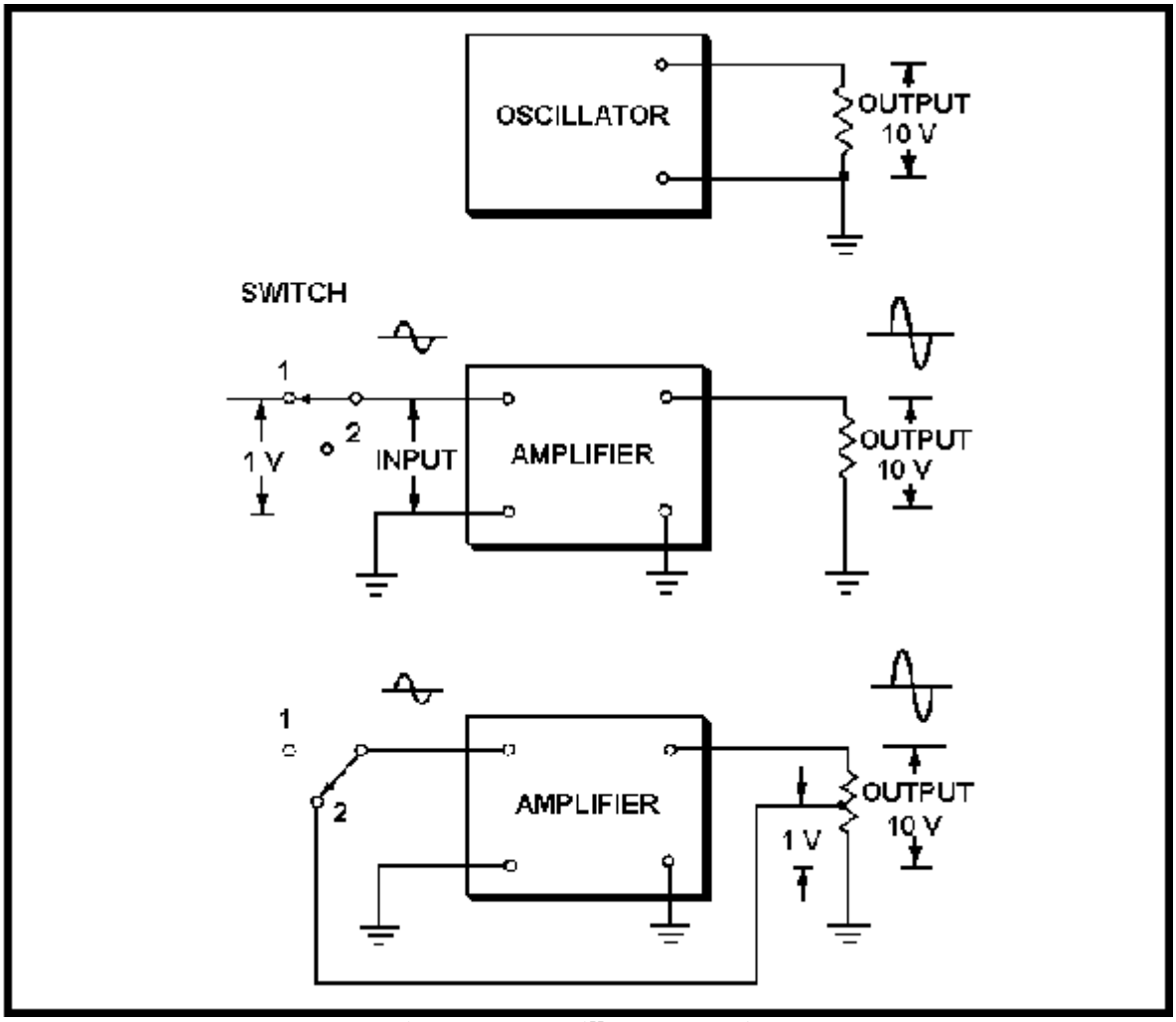

Figure 5-2. Oscillator Operation.

The oscillator should produce an output voltage having negligible distortion, especially if it is to be used in making distortion tests on amplifiers or other equipment. Distortion products originating in the oscillator will appear in the output of the amplifier under test as well as in the circuits of the oscillator itself, and it is difficult or impossible to separate the two. If the oscillator output is appreciably distorted, even a distortion-free amplifier would appear to produce appreciable distortion. Distortion in oscillators is minimized by special circuits and by operating all components conservatively, that is, by not driving any component with excessive current or voltage that might produce distortion.

The following paragraphs describe and explain two oscillator types that can be built to meet the foregoing requirements. They are the RC phase-shift oscillator and the Wien-bridge oscillator.

RC Phase-shift Oscillator. The basic RC phase-shift oscillator may be developed by modification of a conventional amplifier. The amplifier in A of figure 5-3 has a gain of 18 and produces an output of 18 volts when 1 volt is applied to its input terminals, as shown. It differs from a conventional amplifier only in that its load resistor has a phase shifter connected parallel to it. The phase shifter is an RC network. This particular phase shifter takes part of the 18-volt negative-going output voltage of the amplifier and converts it to a 1-volt positive-going voltage--a phase shift of 180°

It is a characteristic of the phase shifter in that it produces exactly these effects at one frequency only. At the one frequency determined by the phase shifter, however, its output is exactly in phase with the amplifier input voltage, as shown by the waveform in A.

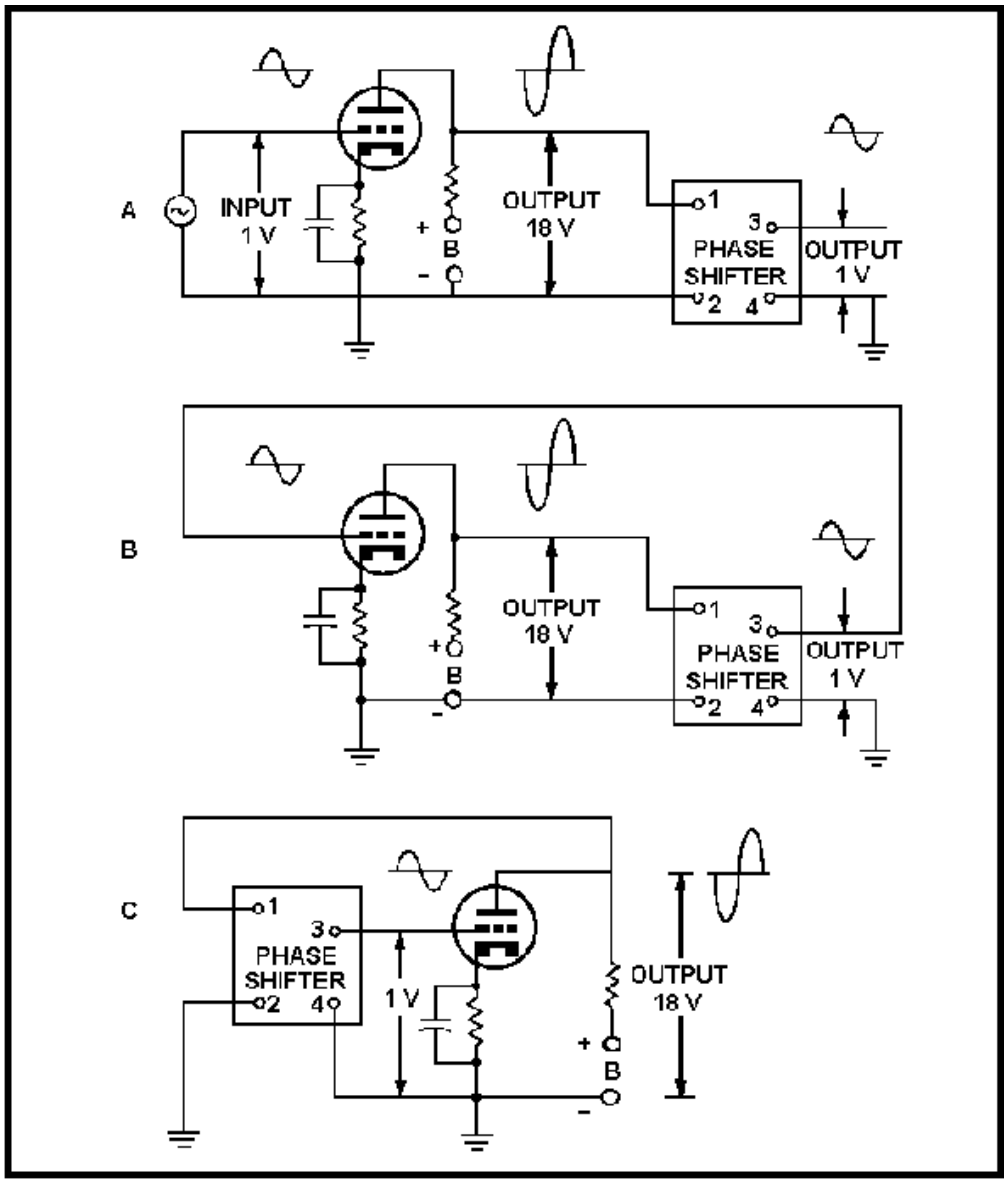

Figure 5-3. Basic RC Oscillator.

In B of figure 5-3, the 1-volt output from the phase shifter has been substituted in the circuit in place of the 1-volt external signal. This meets the requirements for oscillation of an amplifier explained in the preceding paragraph: a proper portion of its output voltage has been fed back to its input in proper amplitude and phase. The oscillator is redrawn in C with the phase shifter shown in a conventional manner on the grid side of the amplifier.

The phase shift of the feedback voltage must be 0^{o}, 360°, or a multiple of 360°, in order to satisfy the phase requirements of an oscillator. This constitutes positive voltage feedback, or regeneration. In the discussion, it is assumed that the one-stage amplifier introduces only 180ø of the required 360°of phase shift. The additional 180° is produced by the phase shifter.

The phase shifter, shown simply as a box in figure 5-3, consists of three resistance-capacitance L-sections, each introducing a phase shift of approximately 60°. One of these L-sections is shown in A of figure 5-4. The L-section consists of a capacitor and a variable resistor in series. Theoretically, this combination can be made to cause a phase difference of any amount from 0° up to 90° between input voltage e and output voltage e_R simply by varying the resistor, and a phase shift of 180° can be obtained by cascading two L-sections (since the phase shifts of cascaded networks add numerically). However, for practical purposes, it is possible to obtain, with one L-section, phase shifts only up to nearly 90°. To obtain 180°, therefore, three L-sections are connected in cascade, each section shifting the phase of the input voltage by 60°.

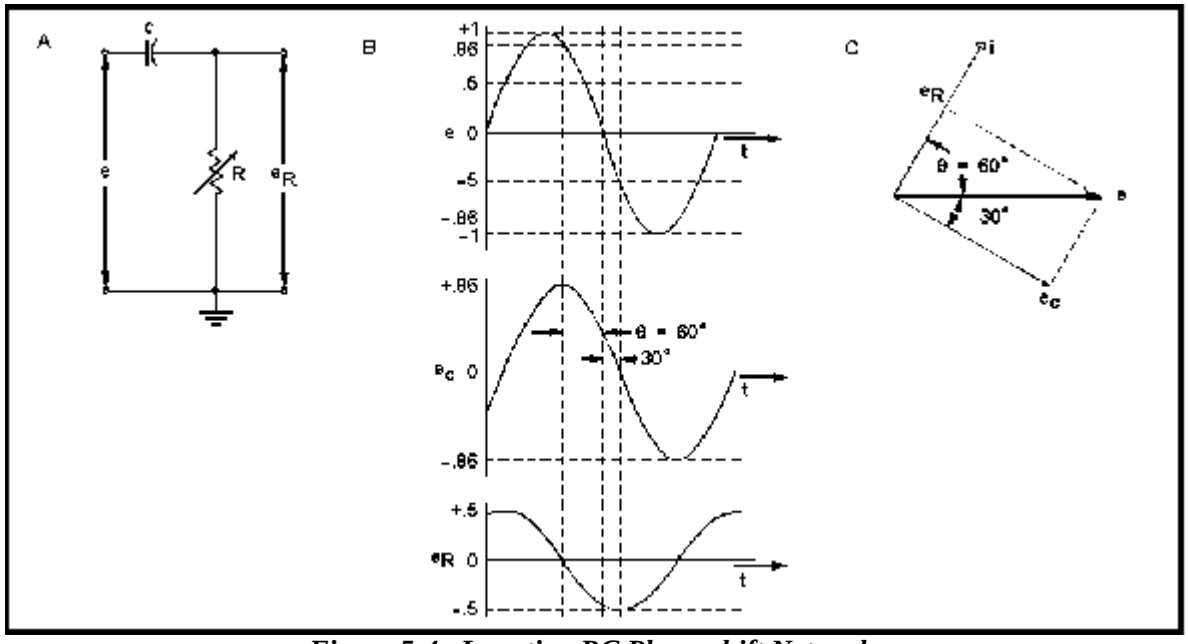

Figure 5-4. L-section RC Phase-shift Network.

In the operation of the L-section as a phase shifter, an alternating voltage, e, is applied to the input terminals. A current flows through the series RC circuit, the magnitude of which is determined by the impedance of the capacitor and resistor. The resulting voltages are represented in the graph in B of figure 5-4 and the vector diagram in C of figure 5-4. Since the impedance is capacitive, the current, i (C of figure 5-4), leads the impressed voltage, e, by an angle shown equal to 60° (in C). The resulting voltage drop, eR, across resistor R, is in phase with the current; and consequently, eR leads the impressed voltage by the same angle.

The phase shift of an L-section can be varied in several ways. For example, varying resistor R changes the phase angle of the current flowing in the circuit. If R is reduced to 0, the phase angle of the current is 90° but this action is useless, because no voltage is developed across 0 resistance. It is possible to get almost, but not quite, 90° in a single L-section of this type. Two practical L-sections can give a phase shift of almost 180°. For this reason, at least three L-sections are needed to obtain 180°.

A combination of three L-sections is shown in A of figure 5-5. The output of section 1 is applied to the input of section 2 that is applied to the input of section 3. Each section contributes to the total phase shift. The phase shift of each section can be adjusted so that each produces 60° of phase shift, making the total phase shift exactly 180°.

The phase relations of the several voltages of a three-section L type of phase shifter are shown in the graph in B of figure 5-5. The output of section 1, eR1, B of figure 5-5, leads the plate voltage, e_p, by 60°. This output is impressed on section 2, output eR2, which leads the plate voltage by twice 60° or 120° Similarly, section 3 adds another 60° of phase shift, making a total of 180°. Thus, the input voltage to the grid leads the output from the plate by 180°. This phase shift is added to the 180° of phase shift contributed by the tube, making the total phase shift 360°.

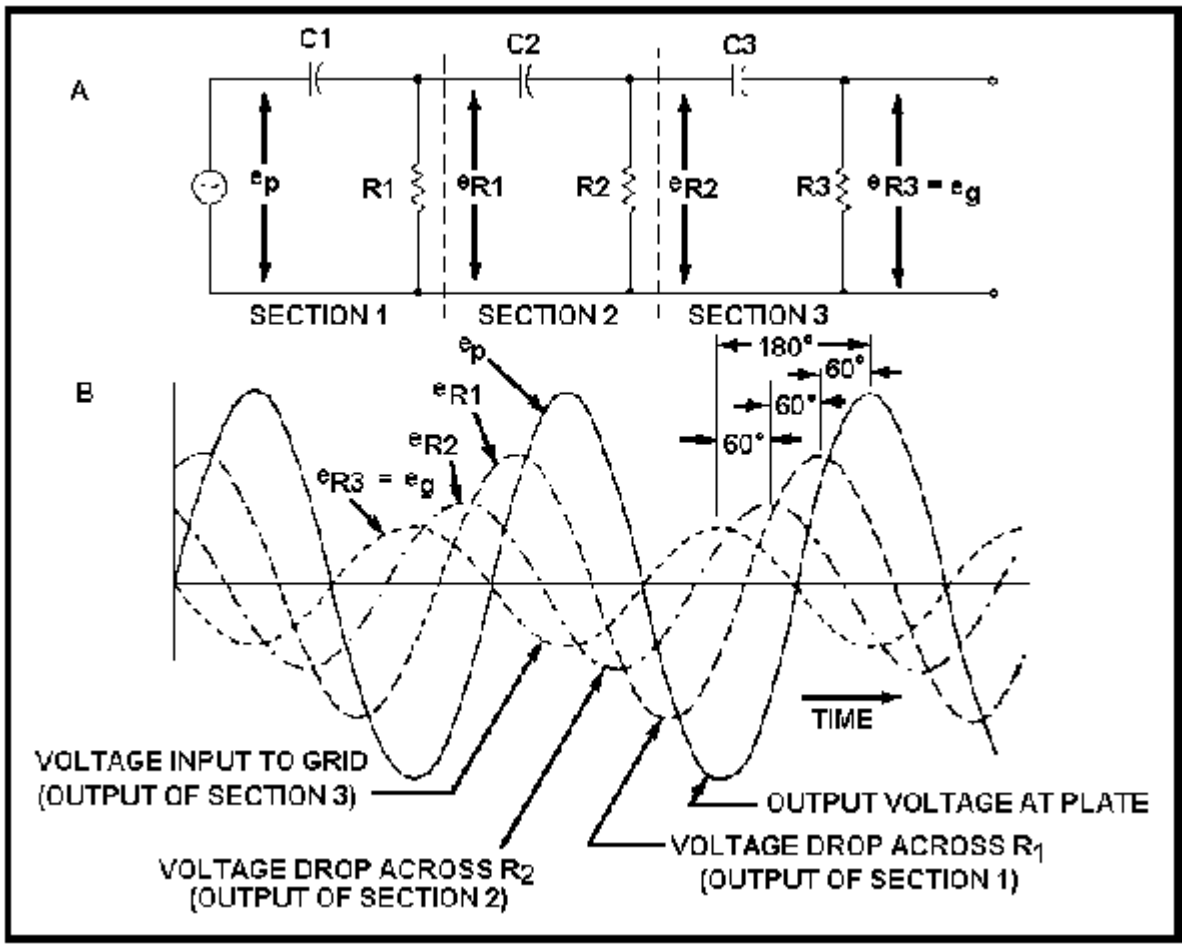

Figure 5-5. Three-section Phase-shift Network.

For practical purposes, the type of phase-shift oscillator employing this three section phase shifter is usually operated at a fixed frequency. Its frequency may be changed, however, by varying the elements of the phase shifter. For example, if the capacitance of any section is increased, the capacitive resistance is decreased.

$$X_C = \frac{1}{2\pi f_C}$$

This causes a decrease in the angle of phase shift provided the frequency is not changed. But at some lower frequency, the capacity reactance and the phase shift will be the same as before. Oscillation can take place only at the one frequency at which the total phase shift is 180°; voltages of any other frequency are fed back out of phase and do not result in oscillation. The frequency of oscillation depends on the ratio Xc/R of each section. If the ratio remains constant, the frequency of oscillation is constant. The frequency is increased by decreasing either the capacitance or the resistance, and vice versa. In practical oscillators, ganged variable capacitors are usually employed to vary frequency smoothly from the lowest to the highest frequency of one range; the resistors are varied in steps that change the frequency range.

RC phase-shift oscillators have several advantages, disadvantages, and modifications.

Advantages. The phase-shift oscillator shown in A of figure 5-6 uses the three-section phase shifter of figure 5-5. This oscillator has many advantages. It is easy to construct, requires only one tube, and operates over a wide-frequency range, from below 1 cycle to about 1 megahertz. This output waveform may be almost a pure sine wave when operated at low gain.

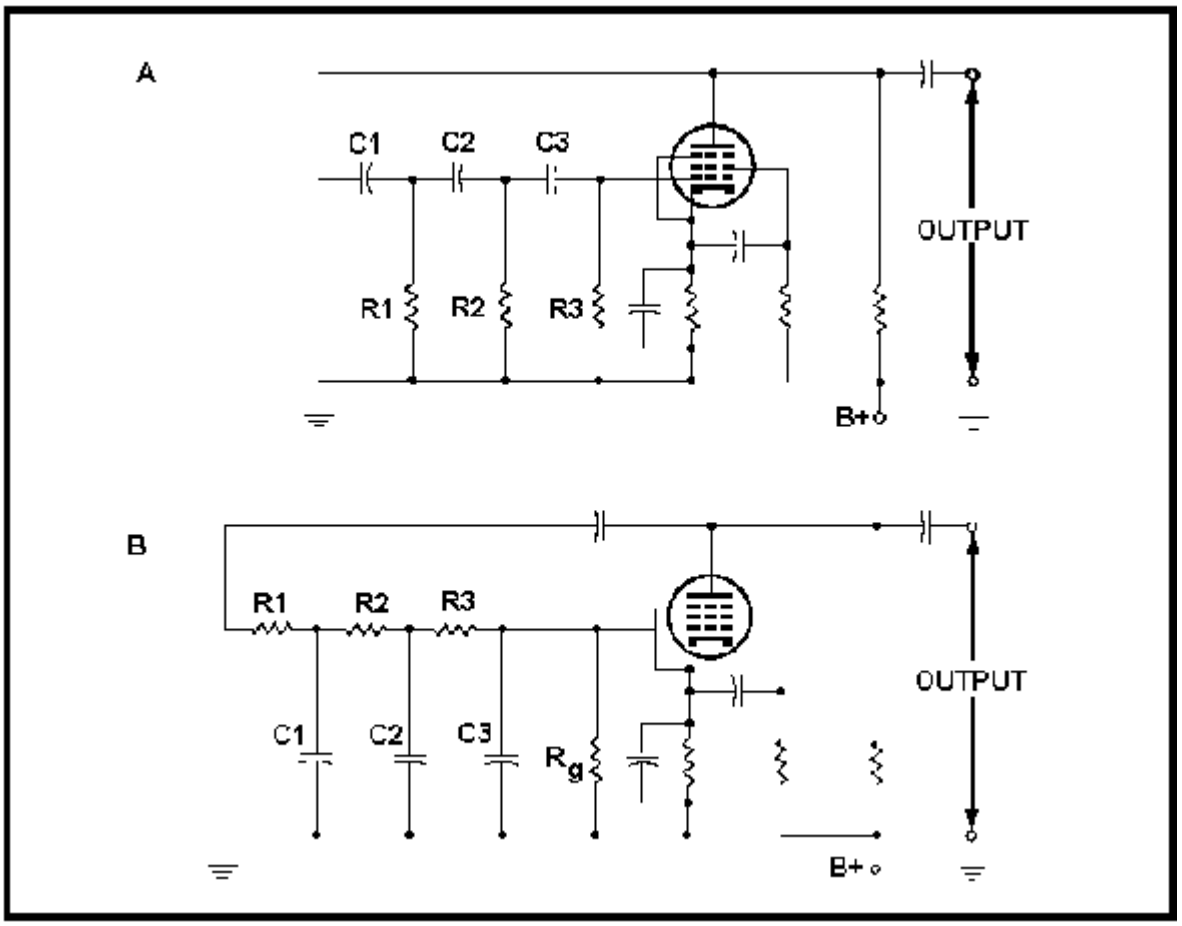

Figure 5-6. Practical Phase-Shift Oscillator.

Disadvantages. The output voltage of the oscillator in figure 5-2 is low in amplitude and it varies as oscillator frequency is varied. Distortion may be high in this oscillator if the tube is operated in the nonlinear portion of its characteristic curve. When this occurs, the tube produces high-frequency harmonics that easily pass through the capacitors in the RC network and are applied to the grid of the tube and reamplified. Thus, the output waveform may contain the harmonics generated by the tubes plus the amplified distortion products.

In order to minimize distortion, the tube must be operated on the most linear portion of its characteristic curve and at low-output voltage. Another disadvantage is the loss that the phase-shift network introduces. For example, the three section L type of phase-shift network requires an input of 29 volts in order to supply an output of 1 volt. The circuit will oscillate only if the tube has a gain higher than the loss caused by the phase-shift network. The tubes used for this oscillator are high in triodes or pentodes. Another disadvantage of the RC oscillator is that the output voltage of the oscillator changes in magnitude as the frequency is varied. This effect is undesirable not only because it is time consuming to check the oscillator output voltage whenever the frequency is changed but also because the amount of waveform distortion of an amplifier (and oscillator) usually changes with amplitude.

Modifications. The phase-shift oscillator circuit in A of figure 5-6 can be modified to remedy its shortcomings. One method that minimizes waveform distortion is shown in B of figure 5-6. Here, the R and C elements of the phase shifter are interchanged. Distortion is reduced because the capacitors are practically as short circuits for harmonics of the fundamental frequency. However, experiment and analysis show that the values of resistors and capacitors needed for this phase shifter are often impractical. One alternative is to use the first phase shifter (shown in A, figure 5-5) and operate it at only one frequency.

Wien-bridge Oscillator. The shortcomings of the phase-shift oscillator are minimized in the Wien-bridge oscillator (figure 5-7). This oscillator is named after its inventor and consists of a network of resistors and capacitors that produce the feedback. The feedback voltage is obtained from a network having zero phase shift at the frequency of oscillation; for this reason, the losses of the network at the frequency of oscillation are lower than the losses of the L type of phase shifter. Since the phase shift of a single tube is only 180° (reversed polarity), it is necessary to use two tubes connected in cascade to provide the 360° of phase shift (same polarity) required for oscillation. The tubes are made part of a two-stage amplifier having two feedback loops. One of these paths provides the positive feedback that causes oscillation; the other provides the negative feedback that minimizes distortion and maintains the output voltage constant over a wide range of frequencies. Because the entire phase shift is provided by the tubes, the actual function of the phase shifter is to control the frequency of oscillation rather than to shift the phase of the feedback voltage.

For an understanding of the operation of the Wien-bridge oscillator, refer to the phase shifter illustrated in figure 5-8. It forms two of the four arms of a Wien-bridge. One arm is the series combination of resistor R1 and capacitor C1; the other arm is the parallel combination of resistor R2 and capacitor C2. Two voltages are of interest in the phase-shifting network (figures 5-8). They are the input voltage, E_i, which is impressed across the entire network, and the resulting output voltage, E_o, which appears across the parallel combination of R2 and C2. Curve 3 of figure 5-9 shows the variations of the phase of the output voltage relative to that of the input voltage. As shown, it leads the input at frequencies below F_o and lags at frequencies above F_o. At F_o the phase shift is zero. This is because the phases of the voltages across the two bridge arms vary in opposite directions as frequency changes. For example, at a frequency below F_o, the voltage across the series arm lags the input, and the voltage across the parallel arm leads the input. As the frequency increases, the phase difference between each of these voltages and the input voltage decreases, until at one critical frequency, F_o, both are in phase with the input. The voltage across the parallel arm is the output voltage.

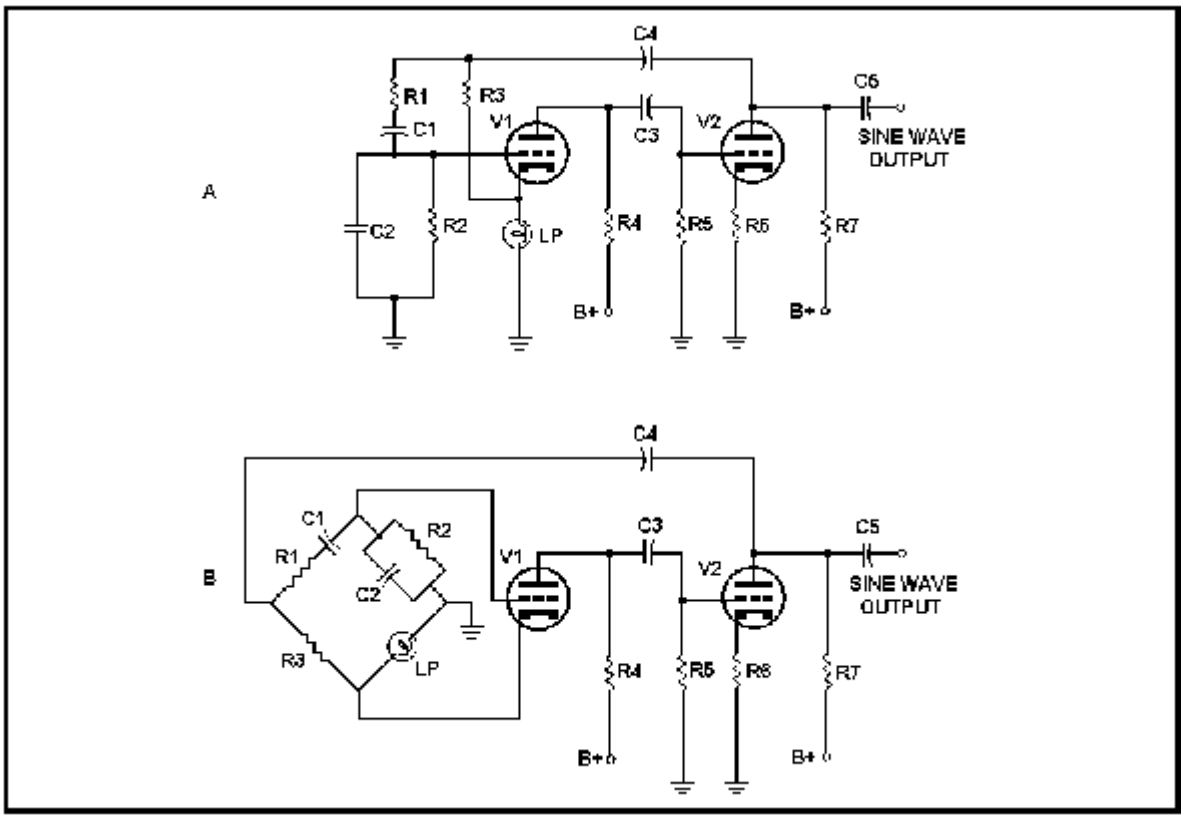

Figure 5-7. Wein-bridge Oscillator.

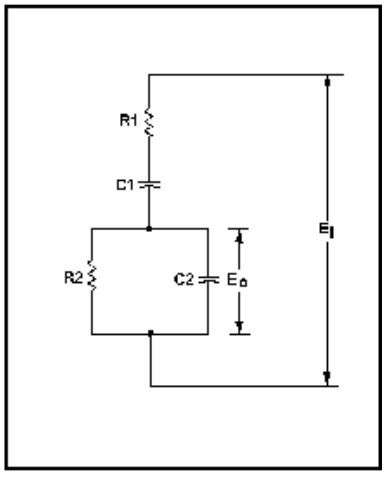

Figure 5-8. Wien-bridge Phase Shifter

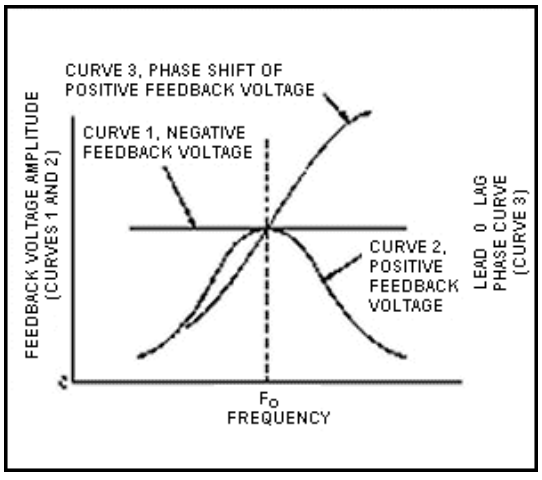

Figure 5-9. Frequency Feedback Voltage in Wein-bridge Oscillator

Both experiment and analysis show that the output voltage of the phase shifter is greatest at the frequency of zero phase shift. It is customary to make the two resistors, R1 and R2, equal, and the two capacitors, C1 and C2, equal (figure 5-8). Under this condition, the maximum output occurring at the frequency of zero phase shift is exactly one third as large as the input voltage. Consequently, only 3 volts are required at the input to the phase shifter in order to obtain a 1-volt output at the oscillating frequency.

Figure 5-10 shows the simple steps required to develop the Wien-bridge oscillator circuit from a two-stage amplifier. Assume that the first stage of the amplifier (A of figure 5-10) has a voltage gain of 50, and the second has a gain of 10. The overall gain of the amplifier is 500, and 1 volt applied to the input terminals of the amplifier should appear as 500 volts at the output.

Note that the output and input voltages are in phase at the frequency for which the phase shift of the amplifier is exactly 360° (same polarity) (A of figure 5-10). Because this is so, the amplifier oscillates if a portion of the output voltage is used to drive the amplifier in place of the external signal generator. One way of reducing the 500 volts of output to the required 1 volt of input voltage is to use a simple resistance voltage divider. In B of figure 5-10, distortion is reduced by applying negative feedback to the amplifier. This reduces the gain to such a value that only the needed 1 volt of input is obtained. It also flattens the frequency response of the amplifier, maintaining both the phase shift and the output voltage almost perfectly constant over a wide-frequency range. For example, the feedback network, R3-R4 (figure 5-10), reduces the overall gain of the amplifier from 500 to about 3 if R4 is made twice the resistance of R3. The output voltage of this amplifier is now 3 volts when 1 volt is applied to the input terminals.

In order to hold the frequency of oscillation constant, the Wien-bridge phase shifter (figure 5-8) is connected between the output of the amplifier and the input (C of figure 5-10). The amplifier oscillates at one frequency because the phase shift between output and input terminals is still 360ø (same polarity), and the phase shifter introduces zero phase shift at that one frequency. For example, the amplifier oscillates at 1,000 hertz if the phase shifter has zero phase shift at 1,000 hertz.

The amplifier also amplifies voltages of other frequencies, but these voltages are reduced by the phase shifter in the positive feedback path to amplitudes less than that of the negative feedback voltage. Therefore, they are cancelled out at the grid, and oscillation at undesired frequencies does not occur. To accomplish this cancellation the overall gain of the amplifier is adjusted to a value of 3. The discrimination of the circuit against all but the desired frequency of oscillation is sharpened by the phase shifter, which applies voltages of undesired frequencies to the grid, out of phase as well as in reduced amplitude.

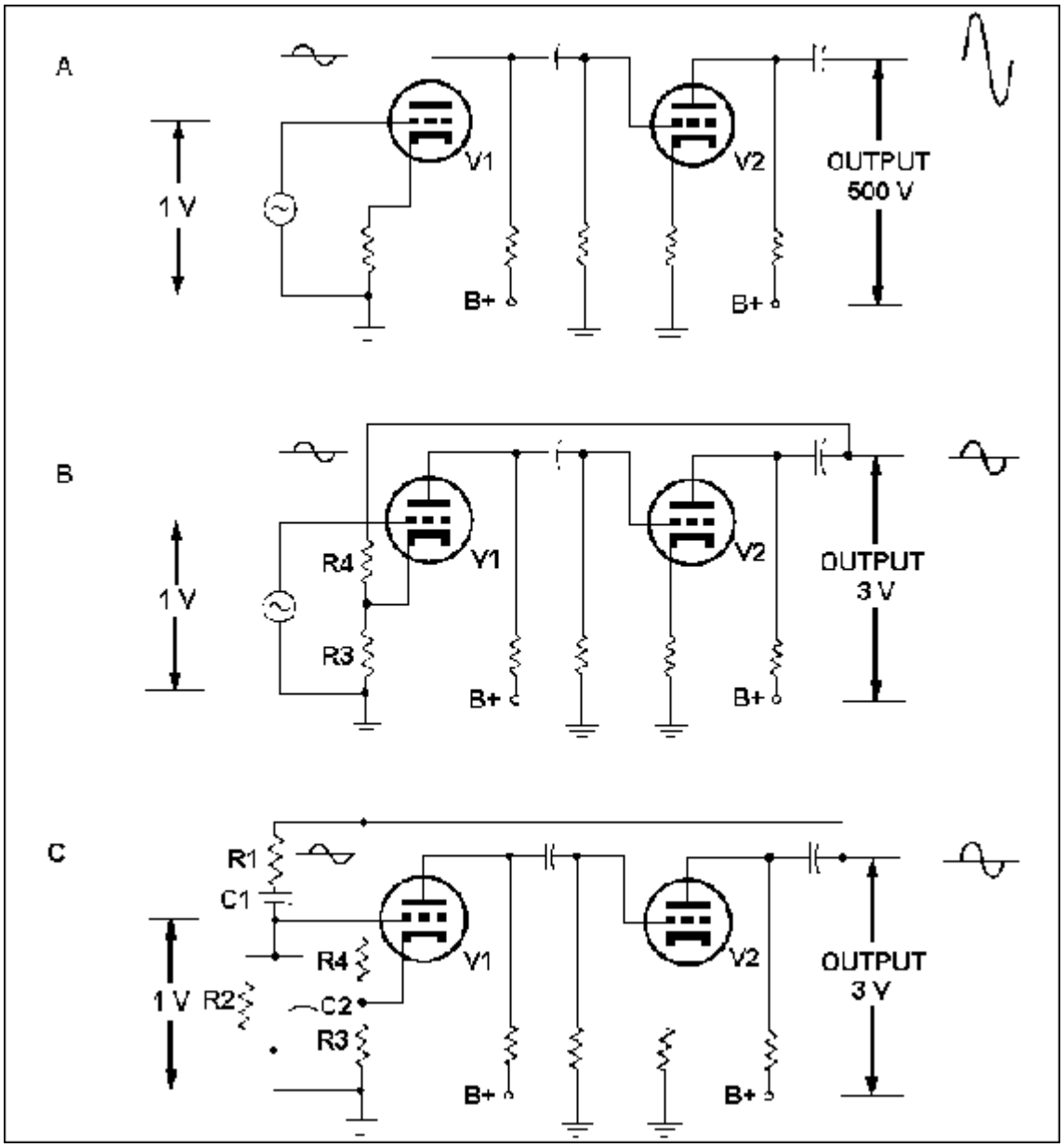

Figure 5-10. Development of Wein-bridge Oscillator.

The oscillator, in C of figure 5-10, is made to operate at any desired frequency by changing the values of the resistances or capacitances of the phase shifter. These values determine the frequency in accordance with the following formula:

$$F = \frac{1}{2\pi R_1 C_1}$$

The formula involves only R_1 and C_1 because the resistances of R_1 and R_2 are equal and the capacitances of C_1 and C_2 are likewise equal. The formula shows that frequency is increased by using smaller values of resistance, or of capacitance, or of both. For example, a typical oscillator has four frequency ranges: 20 to 200 hertz, 200 to 2,000 hertz, 2,000 to 20,000 hertz, and 20,000 to 200,000 hertz. Each range is selected by switching different

resistors into the Wien-bridge, and the frequency is varied smoothly in each range by moving the variable capacitors.

A practical Wien-bridge oscillator usually has one other element that ensures constant output voltage as frequency changes. This is a lamp, or thermistor, as shown in A of figure 5-7. This lamp is used in place of the cathode bias resistor of V1 in A of figure 10. It stabilizes the amplitude of oscillations because its resistance varies with the current that flows through it. The current flowing through the lamp is determined by the feedback voltage impressed across it. This voltage increases if for some reason the output voltage increases. As a result of high-impressed voltage, the filament of the lamp becomes hotter, making its resistance greater; a greater negative feedback voltage is developed across the increased resistance. Thus, more degeneration is provided, which reduces the gain of the amplifier and thereby holds the output voltage at a nearly constant amplitude. The circuit shown in A of figure 5-7 is redrawn in B to show the bridge configuration of the feedback circuit more clearly. The two upper arms comprise the Wien-phase shifter and the two lower arms contain the negative feedback resistor, R3, and the lamp, LP.

INTRODUCTION TO NONSINUSOIDAL OSCILLATORS

Many electrical devices require voltages having nonsinusoidal waveforms, such as sawtooth and square waves, rather than the sine wave voltages. Sawtooth waves are needed in the sweep circuits of oscilloscopes and in many radar and television circuits. Square or rectangular waveforms are used in radar circuits and in other applications to develop trains of pulses or to operate gating circuits and electronic switches. Sawtooth generators, multivibrators, and blocking oscillators are nonsinusoidal oscillators and operate by charging and discharging through a resistance. An elementary form of sawtooth generator will be discussed first, since it affords the simplest illustration of the principle underlying each one.

A sawtooth waveform is used in oscilloscopes in order to deflect, or sweep, the electron beam back and forth across the screen of the cathode ray tube at a constant rate. The resulting visible trace on the screen is known as a sweep, or time base. The beam moves from left to right across the screen at a constant and relatively slow rate and then returns more quickly to its starting position at the left. It then repeats the same back and forth excursion at a definite frequency. This motion of the beam is caused by a voltage that varies with time, as shown in figure 5-11. The instantaneous value of the voltage increases at a constant and relatively slow rate, falls more quickly to its initial value, and then repeats the cycle indefinitely.

Sawtooth voltages are generated in oscillator circuits using tubes to control the charge and discharge cycle of a capacitor. The resulting voltage across the capacitor is a sawtooth waveform. The tubes may be either gas-filled or vacuum. Oscillators using vacuum tubes are more widely used because of their greater frequency range, better linearity, and more stable operation. Gas tube oscillators, however, are very simple.

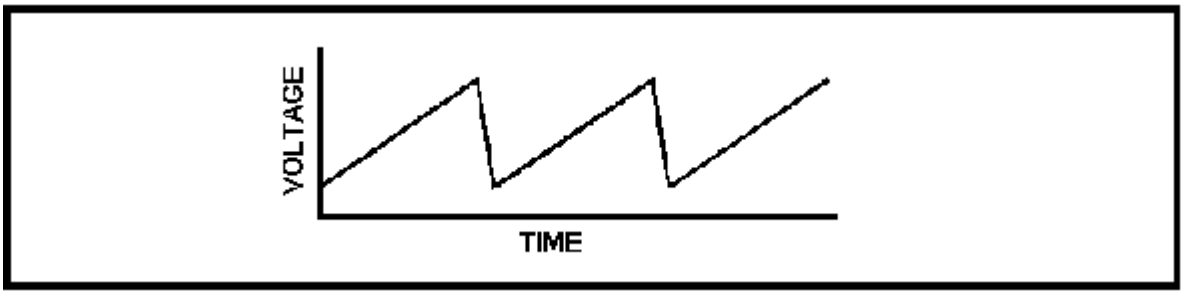

Figure 5-11. Sawtooth Voltage Waveform.

Gas Diode Oscillator

Basic Oscillator. The simplest sawtooth oscillator is one employing a gas diode. It is unstable in frequency, which limits its application. An understanding of its operation, however, provides a foundation for the study of other nonsinusoidal oscillators. Figure 5-12 (A) shows the three essential elements of a gas diode oscillator circuit; a capacitor, C; a series resistor, R; and a gas-filled diode. They are connected as shown and supplied from a dc voltage source. The diode is a neon-glow lamp, the type commonly used for indicating purposes. It consists of two electrodes mounted in a small glass envelope filled with neon gas. There is no heater or filament supply; the tube operates with a cold cathode. The circuit produces sawtooth oscillations when the dc voltage, E, is applied. The supply voltage causes a current flow through the series resistor, R, into the capacitor, C. The voltage across the capacitor rises according to the exponential charging curve shown in figure 5-13. As the capacitor charges, the voltage across it approaches the supply voltage. The voltage across the neon tube is the same as the voltage across the capacitor, because these elements are parallel. The neon tube acts as an open switch until the voltage across it reaches a critical value called the firing voltage or firing potential.

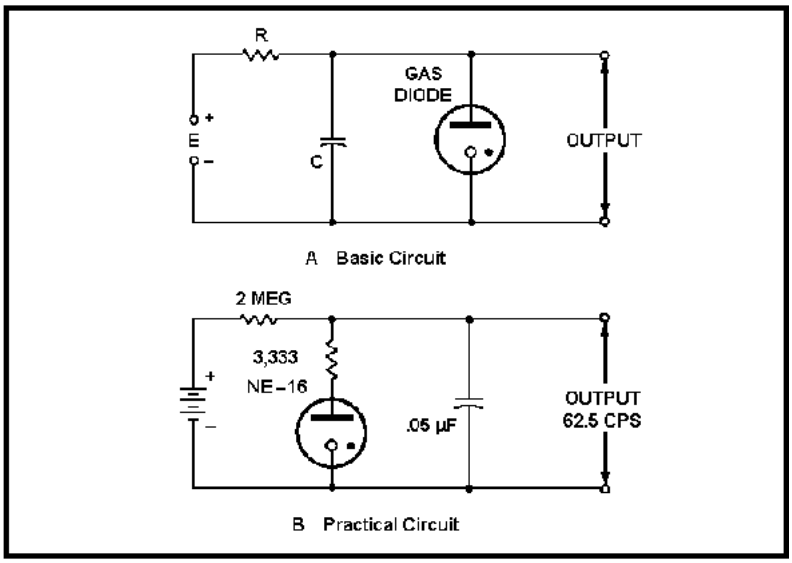

Figure 5-12. Gas Diode Oscillators.

At this point, the gas in the tube ionizes and conducts rapidly, which makes the tube act like a very low resistance across the capacitor. The capacitor thus discharges very rapidly, as shown by the discharge curve. The discharge stops when the voltage across the tube and capacitor reaches the deionizing potential of the tube. At this voltage, conduction stops. The tube again becomes an open circuit and the capacitor begins to change again; the voltage across it increases as shown by the second rise in the unbroken curve (figure 5-13). Again, the voltage drops sharply when it reaches the firing potential. This process continues as long as the dc supply is maintained and produces the succession of sawtooth waves of voltage across the capacitor shown in the figure. Note that the capacitor charging curve is a slightly curved line that prevents the sawtooth curve from having a perfect triangular shape.

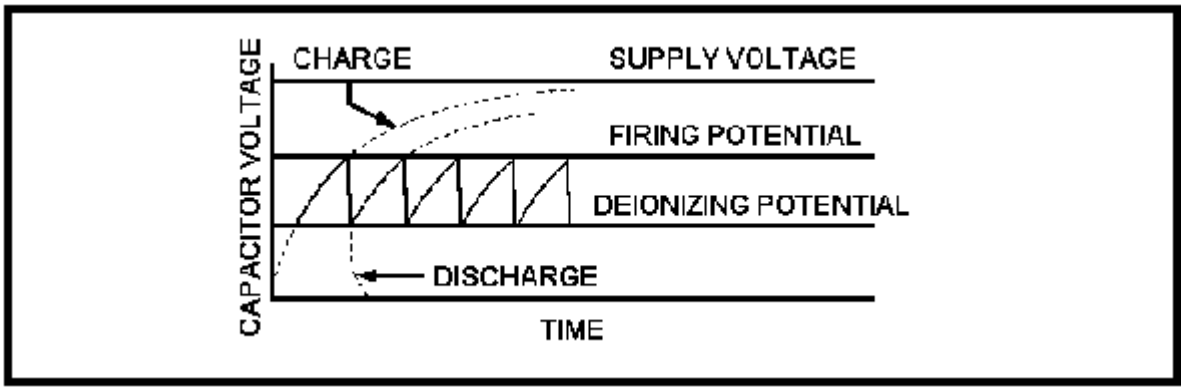

Figure 5-13. Variation of Capacitor Voltage in Neon Sawtooth Generator.

Practical Oscillator. The simple circuit shown in A of figure 5-12 is impractical because when the neon tube starts conducting, its resistance is momentarily very small and permits excessive current to flow, damaging the tube. This defect is eliminated in the circuit of B, where a protective resistor is inserted in series with the tube to limit the peak current to a safe value. The tube in figure 5-12 is an NE-16 neon lamp, which fires at about 77 volts and deionizes at about 48 volts. (Because these voltages may differ by several volts in different tubes, it is impossible to accurately predict the operating characteristics of the circuit.) The frequency of a sawtooth wave is the number of times the voltage rises and falls per second. Frequency is controlled by varying the time constant of the circuit or the magnitude of the supply voltage (figure 5-14). The time constant depends on the values of the charging resistor and the capacitor.

Thyratron Sawtooth Oscillators

As a rule, whenever nonsinusoidal waves are used in electronic circuits, their frequency must be accurately controlled or synchronized with a signal of known frequency if the waves are to serve a useful purpose. For example, the sawtooth waves that generate the sweep voltage of an oscilloscope must be held at a constant known frequency in order that a steady pattern may be seen on the screen.

Thyratron Tube. The frequency of a sawtooth oscillator can be controlled with great accuracy by using a special gas triode known as a thyratron. The operating characteristics of this tube differ considerably from those of vacuum triodes.

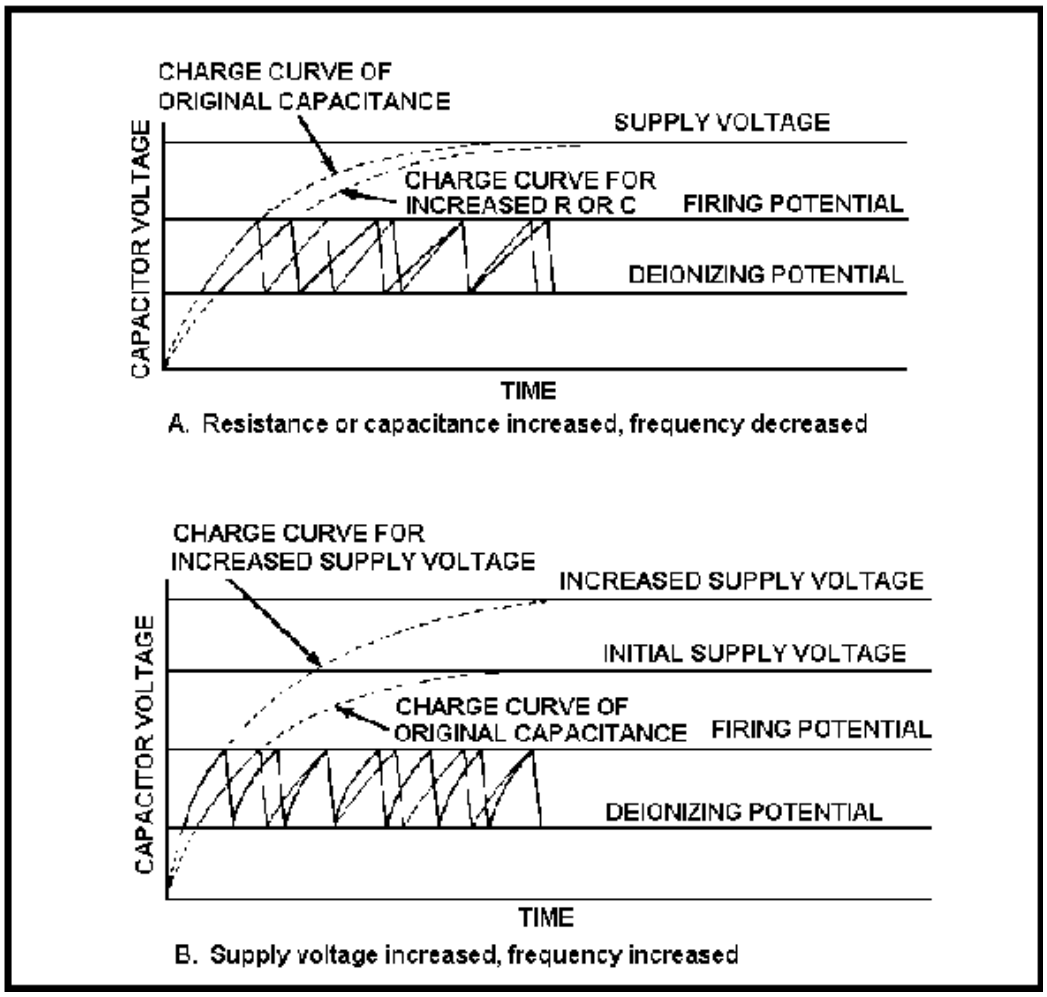

Figure 5-14. Frequency Changes resulting From Changes in Circuit Constants of Neon Sawtooth Generator.

Like a vacuum triode, a thyratron has a grid as its third element, but there are differences in both the physical structure of the two grids and in their effect on the plate current. In a vacuum triode (assuming a fixed-plate voltage), the voltage applied to the grid controls not only whether plate current flows or not but also how much current flows. In a gas triode, the grid voltage can merely turn the plate current on. Once plate current starts, the grid voltage exercises no control over the amount of plate voltage. The grid functions as a switch by altering the firing potential of the tube. The higher (more positive) the grid voltage, the lower the plate voltage required to ionize the gas in the tube and start conduction. Thus, a thyratron that is cut off may be made to conduct by increasing sufficiently either the grid voltage or the plate voltage. For any given grid voltage, the thyratron functions as a gas diode, regardless of grid voltage. Conduction stops only when the plate voltage falls to the deionization potential. The manner in which the grid and plate voltages of a typical thyratron controls its functioning is shown in figure 5-15. The graph shows the firing plate voltage for a range of values of negative grid voltage. For example, if the grid voltage is -20 volts, the tube will conduct or fire when the plate voltage is slightly under 160 volts. But, if the grid voltage is raised to -12 volts, the tube will fire with only 100 volts on the plate. The thyratron differs from the neon gas tube, also, because the plate current rating in thyratrons is greater. Typical values range from 125 ma in a small thyratron up to many amperes in a heavy duty tube.

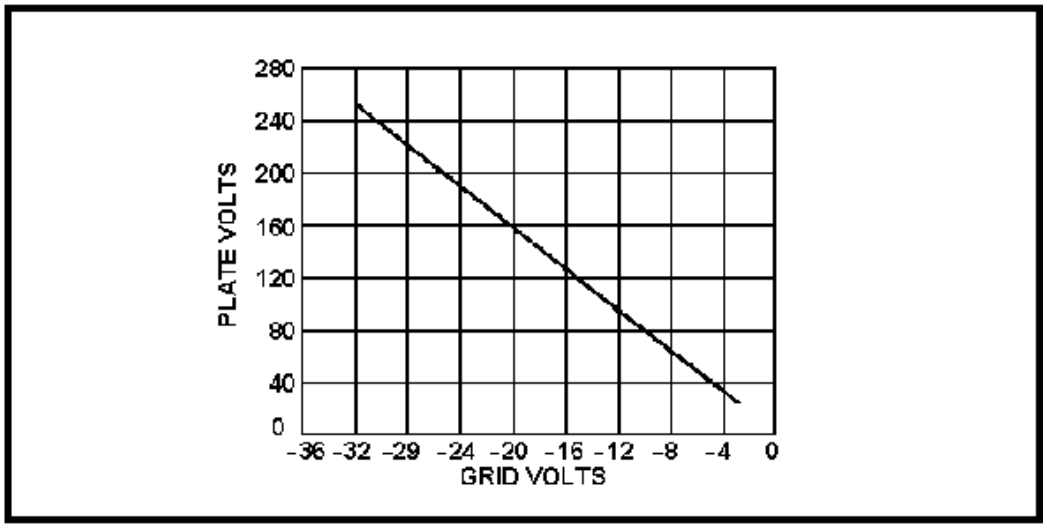

Figure 5-15. Plate-voltage and Grid-voltage Characteristics of Typical Thyratron.

Thyratron Circuit. In A of figure 5-16, the thyratron sawtooth oscillator circuit resembles the diode oscillator circuit of figure 5-12. This circuit is redrawn in B, as conventionally shown in schematic diagrams. The triode and diode circuits differ only in the values of the elements and in the additional connection required for the bias voltage on the thyratron grid. For the circuit shown, the bias is -6 volts.

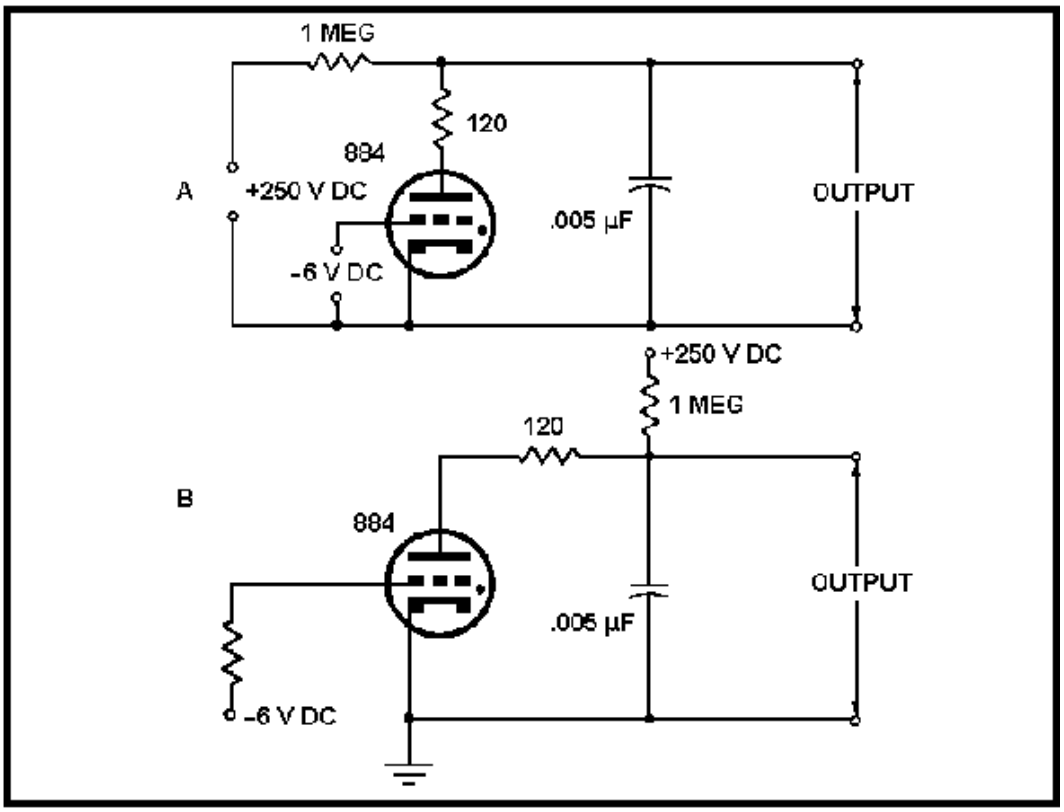

Figure 5-16. Thyratron Sawtooth Oscillator.

The protective resistor is small--120 ohms--because of the larger current that the thyratron can carry safely. For the operating conditions specified for this circuit, the rated peak current of the tube is 300 ma. A larger protective resistor is needed if the bias is increased (made more negative); however, because this raises the firing voltage, the values of the charging resistor and capacitor are chosen to fix the frequency of oscillation at 1,250 hertz. A thyratron oscillator can produce good sawtooth waves at higher frequencies than are possible with a neon tube oscillator. The higher current rating of the thyratron enables it to discharge a capacitor many times more quickly than a neon tube discharges and, therefore, many more cycles can take place each second without violating the requirement that the discharge time be less than the charge time. Practical thyratron oscillator frequencies range up to about 40,000 hertz. Above this frequency limit, thyratrons deionize erratically and other oscillator circuits are used. The frequency of this oscillator is increased if the value of either the capacitor or the resistor, or of both, is reduced. As indicated in figure 5-14, a change of resistance or capacitance in the neon sawtooth oscillator has no effect on the amplitude of the sawtooth. Figure 5-17, however, shows that a change of dc grid bias on the thyratron sawtooth oscillator changes both the frequency and the amplitude of the sawtooth. A greater negative bias in the thyratron has these two effects: it increases the amplitude of the sawtooth voltage across the capacitor because the tube fires at a higher voltage, and it reduces the frequency because a longer time is required for the capacitor to charge to the higher firing potential. Conversely, a smaller negative bias in the thyratron reduces the output voltage and increases the frequency.

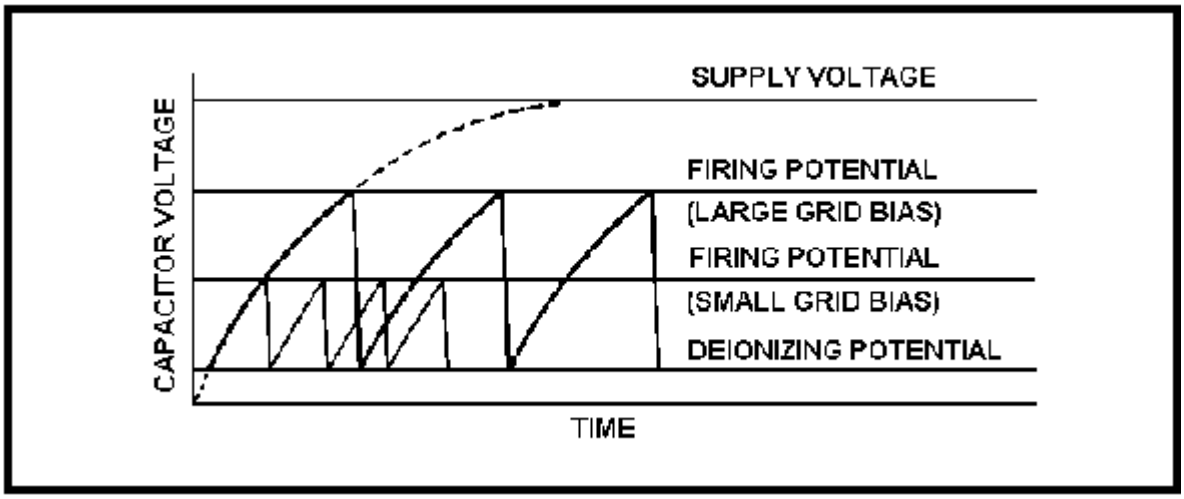

Figure 5-17. Change of Amplitude and Frequency by Change of Grid Bias.

Synchronization of Thyratron Oscillators. In time-base applications and in other electronic circuits, it is often necessary to use a sawtooth wave, the frequency of which remains constant, or remains exactly in step, or in synchroization, with another frequency. The frequency at which the thyratron normally oscillates is called the uncontrolled frequency or freerunning frequency. However, if a small voltage of the desired frequency is injected at the grid of the thyratron, the circuit will oscillate at this frequency, instead of its free-running frequency. When this is done, the oscillator is said to be synchronized with the injected voltage.

The circuit of the synchronized thyratron oscillator is shown in A of figure 5-18. Its operation is as follows: the charging resistor, R1, and the capacitor, C2, are adjusted for a free-running frequency slightly lower than that of the synchronizing voltage. For example, if the synchronizing voltage frequency is 60 hertz, the free-running frequency of the thyratron is set to about 58 hertz. The synchronizing action is illustrated in B. The dc bias is set by the potentiometer, R2. Without the synchronizing voltage, the firing potential is constant, and the tube fires at point A where the peak of the broken-line sawtooth intersects the constant firing potential line of the tube. When the synchronizing voltage is present on the grid, however, the firing voltage and the plate voltage vary in accordance with the grid signal. In B of figure 5-18, it is assumed that the synchronizing voltage is a sine wave, but this is not a necessary operating condition. At some time during the synchronizing cycle, the varying firing potential is lowered so that the tube fires at a slightly earlier instant, represented by point B, where the peak of the unbroken-line sawtooth meets the varying firing potential curve.

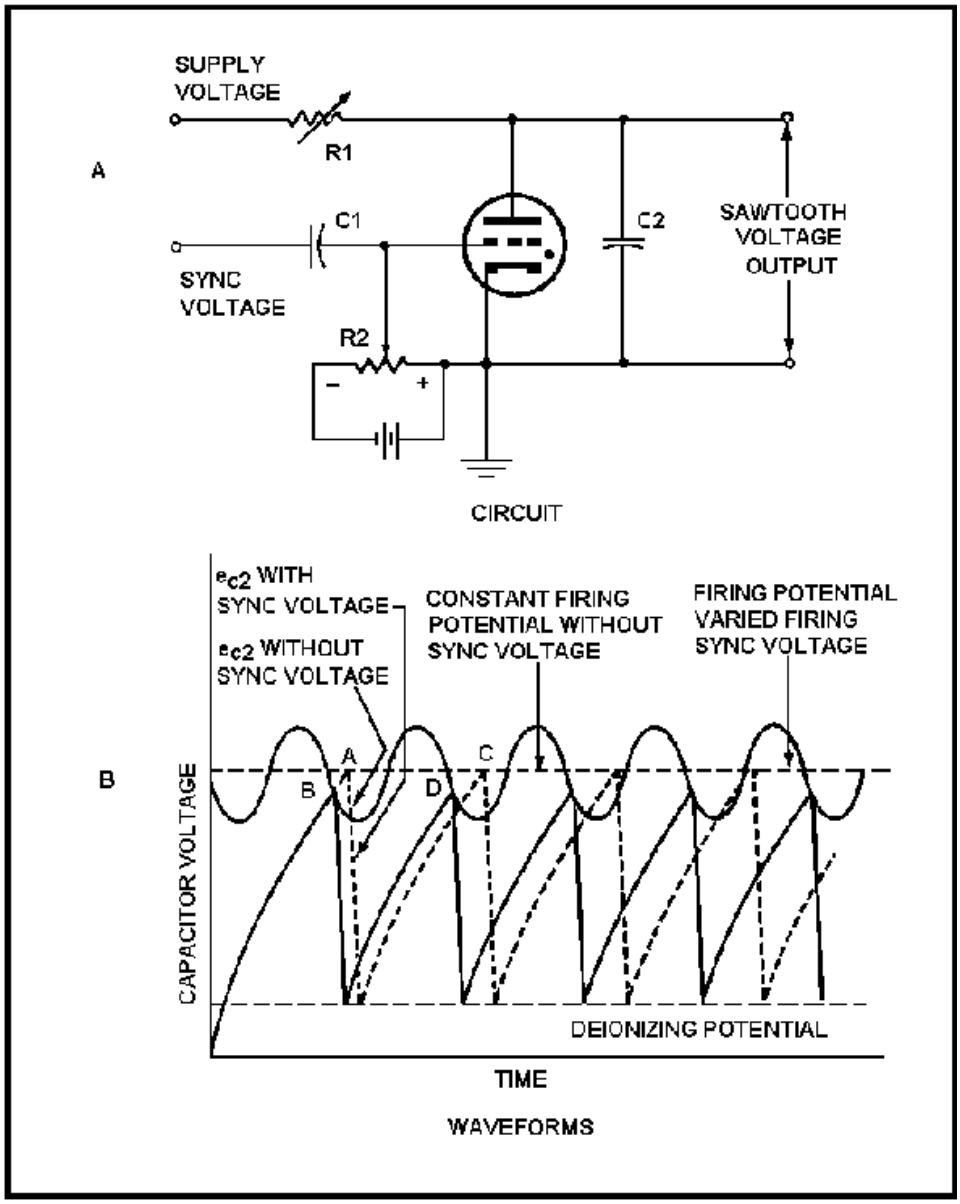

Figure 5-18. Synchronized Thyratron Sawtooth Oscillator.

On the next cycle, the capacitor voltage again reaches the firing point earlier than it would without the synchronizing voltage at the instant represented by point D on the unbroken-line sawtooth wave peak. The time of each oscillation is thus reduced from interval AC to interval BD, and the oscillator is locked to the frequency of the injected ac voltage.

Thyratron Switch. One of the many applications of thyratron oscillators is a circuit called a thyratron switch in which two thyratrons are switched on and off alternately by an ac input voltage. By strict definition, this circuit is not an oscillator since it delivers no output when the ac input is removed. When the input voltage is applied, however, the thyratron switch delivers an output having a waveform substantially independent of the input waveform, much as a synchronized thyratron oscillator delivers a sawtooth output regardless of the waveform of the synchronizing voltage. Both circuits depend on the charging and discharging of capacitors, controlled by the switching action of thyratrons. The characteristics of the two circuits differ in several respects. The frequency of the thyratron switch is determined primarily by the frequency of the input voltage, and the output remains in synchronization with the input over wide ranges of frequency variation. The amplitude of the thyratron switch output is constant regardless of amplitude variations of the input. Thyratron switches are used in many types of military electronic equipment.

Circuit Description. Figure 5-19 shows the circuit of the thyratron switch. The output of amplifier tube V1 is coupled by transformer T1 to the grids of thyratrons V2 and V3 through protective resistors R. The dc grid bias is applied between the center tap of the transformer secondary and the thyratron cathodes. Across the plates of the tubes is connected a capacitor, C1. Each of the thyratron plates, V2 and V3, are also connected to load resistors R2 and R3, respectively. The dc plate potential for the two thyratrons is applied to the junction of the two load resistors.

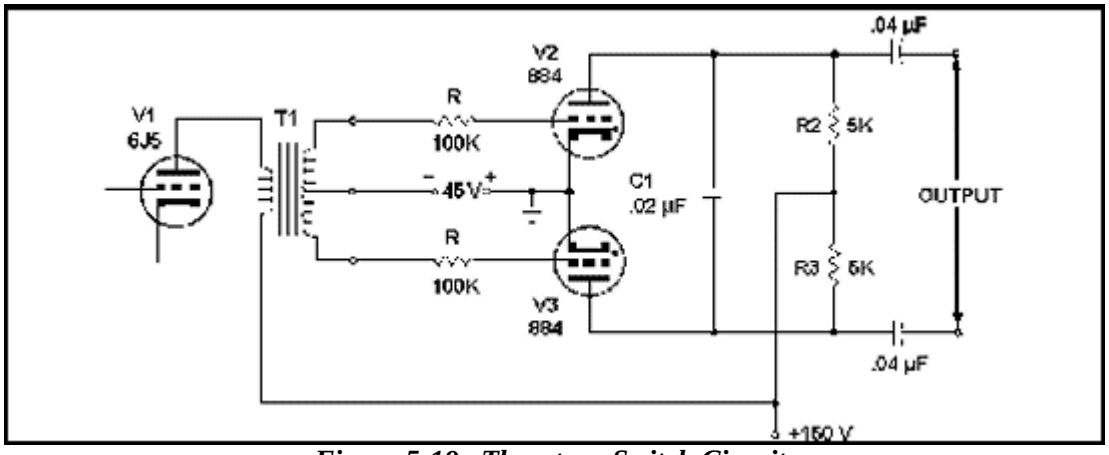

Figure 5-19. Thyratron Switch Circuit.

Operation of Thyratron Switch. The output waveform depends primarily on the circuit, not on the input. Accordingly, the input voltage may be of almost any waveform. For purposes of this explanation, it is assumed that the input is a modified square wave, shown in A of figure 5-20, derived from tube V1and applied across the primary of transformer T1 (fig 5-19). The voltage induced in the secondary winding has approximately the same waveform and amplitude as the transformer input. The center-tapped secondary acts as a phase splitter, delivering two equal voltages, opposite-going in respect to the center tap, as in B and C of figure 5-20. Thus, during the first half-cycle of the ac applied to the primary of the transformer, the grid of one thyratron tube becomes more positive and the tube fires, whereas the grid of the other tube becomes more negative. During the second half-cycle, the polarities of the grid voltages reverse, and the second tube fires. The voltages at the plates of the thyratrons are substantially independent of the waveforms of the grid voltages, as in D and E of figure 5-20.

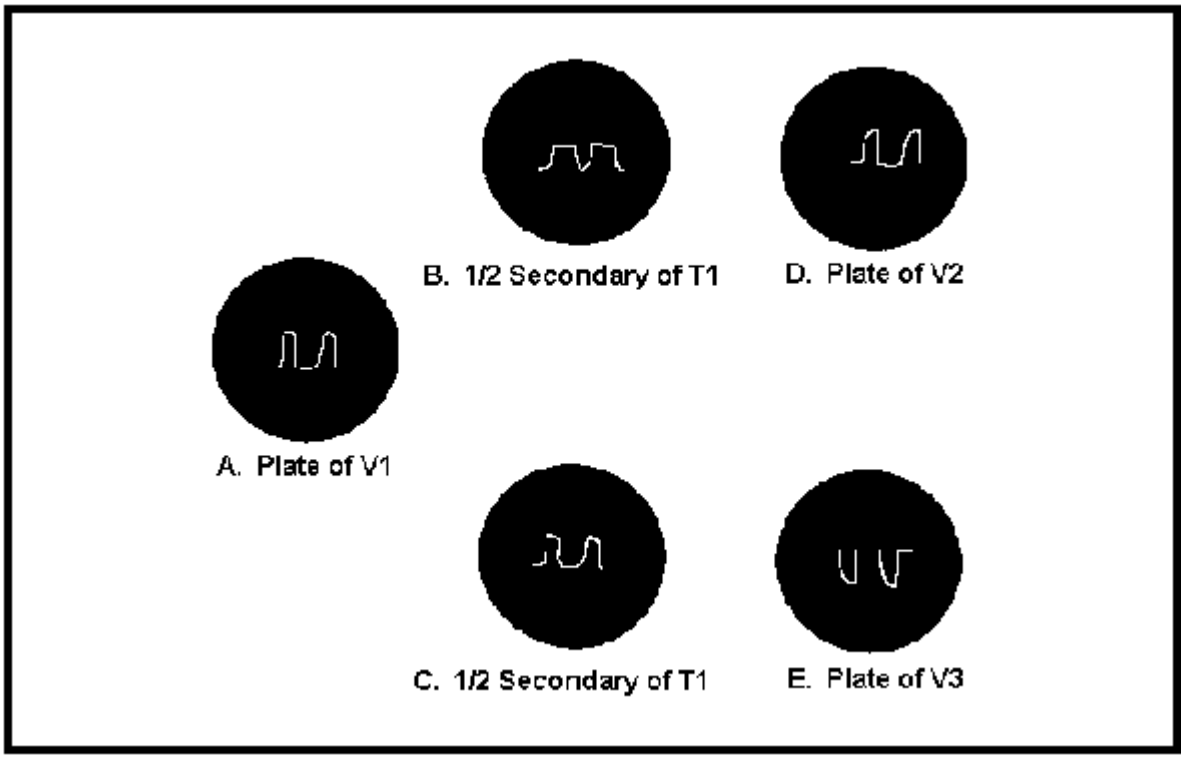

Figure 5-20. Waveforms in Thyratron Switch.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What phase shift, in degrees, is produced at the output of three series-connected L-type phase-shift networks?

   a. 90 degrees.
   b. 180 degrees.
   c. 270 degrees.
   d. 360 degrees.

2. Why is a thermistor used in an oscillator circuit?

   a. To stabilize output voltage.
   b. To stabilize output frequency.
   c. To control the resonant frequency.
   d To control the feedback voltage.

3. What initiates oscillation in a practical oscillator?

   a. Variations in grid current without feedback.
   b. Positive input trigger.
   c. Negative input trigger.
   d. Variations in plate current through feedback.

4. What is the output waveform if a square wave synchronization voltage is applied to the grid of a thyratron oscillator?

   A. Sine.
   b. Square.
   c. Sawtooth.
   d. Trapezoidal.

5. What controls the frequency of a thyratron oscillator?

   a. Frequency of feedback signal.
   b. Frequency of line voltage.
   c. Frequency of input voltage.
   d. Frequency of resonant signal.

6. What components are contained in one L-section of the L-type phase shifter?

   a. Capacitor and variable inductance in parallel.
   b. Capacitor and variable inductance in series.
   c. Capacitor and variable resistor in parallel.
   d. Capacitor and variable resistor in series.

7. What is a disadvantage of the phase-shift oscillator?

   a. Poor high-frequency compensation.
   b. Low-output amplitude.

c. Low-output frequency.
d. Poor low-frequency compensation.

8. What is the advantage of a Wien-bridge oscillator over the phase-shift oscillator?

a. Output voltage varies as frequency is changed.
b. Network losses are lower at the frequency of oscillation.
c. Radiation losses are lower at the frequency of oscillation.
d. Output frequency varies as voltage is changed.

9. What is the function of the phase shifter in a Wien-bridge oscillator?

a. To shift the phase of feedback voltage.
b. To shift the phase of output voltage.
c. To control the amplitude of oscillation.
d. To control the frequency of oscillation.

10. When does an amplifier perform as an oscillator?

a. When output is fed back in phase with input.
b. When a constant positive signal is applied to the input.
c. When a constant negative signal is applied to the input.
d. When output is fed back out of phase with input.

11. What limits the application of a gas diode oscillator?

a. Amplitude instability.
b. Frequency instability.
c. High-firing potential.
d. High-ionization point.

12. What is the frequency limitation, in hertz, of the thyratron oscillator?

a. 80,000 hertz.
b. 70,000 hertz.
c. 50,000 hertz.
d. 40,000 hertz.

13. In what system are sawtooth oscillators primarily employed?

a. Gating.
b. Peaking.
c. Sweep.
d. Clamp.

14. What shift is produced by each section of L-type phase shifter in an operational RC oscillator?

a. 90 degrees.
b. 60 degrees.
c. 45 degrees.
d. 30 degrees.

15. What happens if resistor R1 is increased in the oscillator circuit of C in the figure below?

a. Output voltage decreases.
b. Output voltage increases.
c. Output frequency decreases.
d. Output frequency increases.

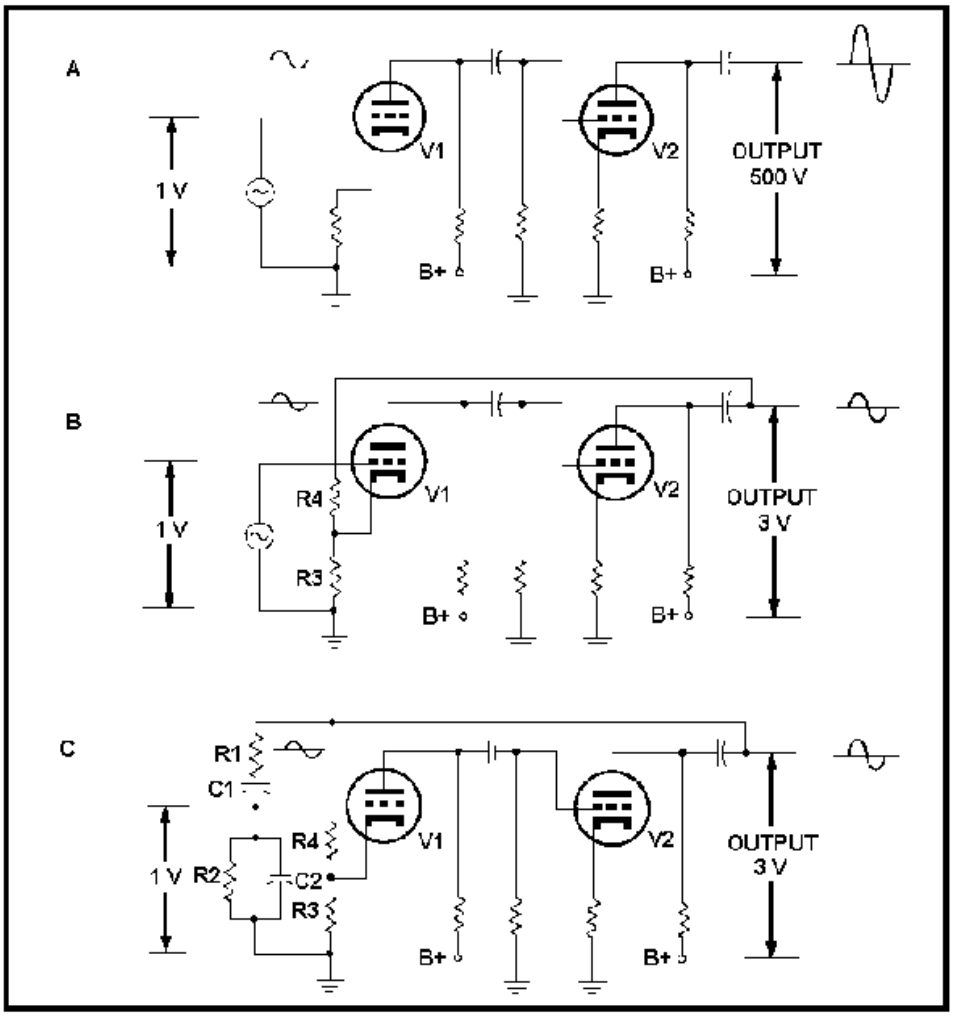

Figure 5-21.

Recheck your answers to the Review Exercises When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 6
AMPLITUDE MODULATION

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to describe the fundamentals of amplitude modulation, sidebands, and types and percentage of modulation.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 70 on the end-of-subcourse examination that covers this lesson and lessons 1, 2, 3, 4, 5, and 7.

TYPES OF TRANSMITTERS

Simple Unmodulated Transmitters

The most elementary unmodulated continuous wave (CW) transmitter consists of any sine wave oscillator covered in lesson 5 connected to a radiating device (antenna). Figure 6-1 depicts this simple CW transmitter with its unchanging output. Although this device will transmit, it is not practical for two reasons. First, it will not transmit far enough to be of any great use; second, when the antenna is connected to the oscillator, the frequency of oscillation will probably shift due to the additional load presented by the antenna.

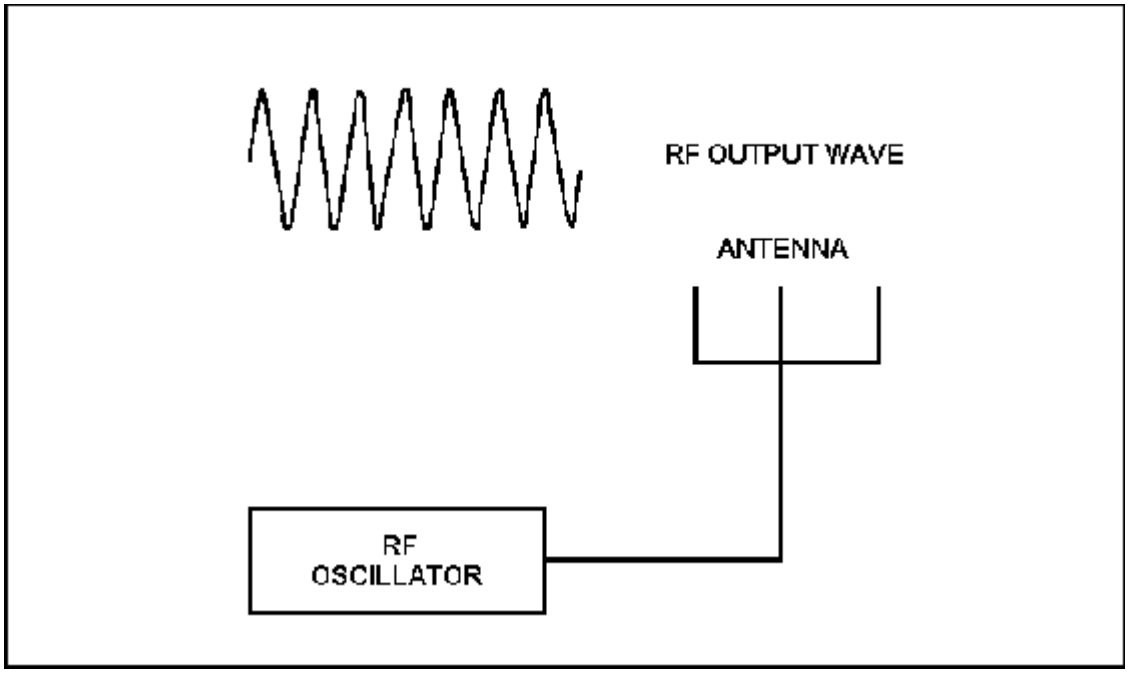

Figure 6-1. Simple Transmitter.

An easy solution to the two problems just described is to add one, two, or three stages of amplification between the antenna and oscillator as shown in figure 6-2. These amplifiers are classified as power amplifiers; the one closest to the antenna is called the final power amplifier, the one closest to the oscillator is called the buffer amplifier, and the third (if any) is called the second power amplifier. The buffer amplifier gets its name because it isolates the oscillator from the remainder of the transmitter or acts as a buffer zone. The input circuit in the buffer amplifier is designed to match the out put of the oscillator so as to load the oscillator and interfere with the oscillator output frequency.

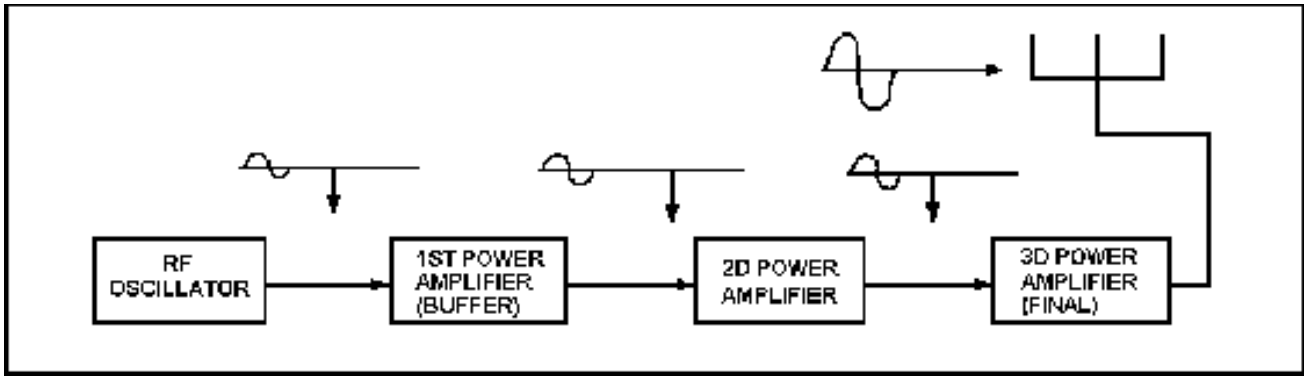

Figure 6-2. Addition of Power Amplifiers to Simple Transmitter.

Practical Transmitters

If a home radio received a CW (unmodulated) signal at a frequency of 150,000 hertz, it would not be audible. In order for a transmitter output to be picked up and heard on a receiver, it must contain some audio-frequency components. The process of combining audio frequencies with radio frequencies, prior to transmission, is called amplitude modulation. The part of the transmitter that accomplishes this task is called the modulator (figure 6-3). The transmitter in figure 6-3 is sending out a radio-frequency wave that has been combined with an audio-frequency wave. If the audio-frequency wave is constant in frequency, a tone on the receiver will be heard, but the constant sound will not convey any information. One method of transmitting information is by the use of a key (figure 6-3) or manually operated switch that interrupts the transmitter output in order to form dots and dashes, enabling Morse code to be sent and received.

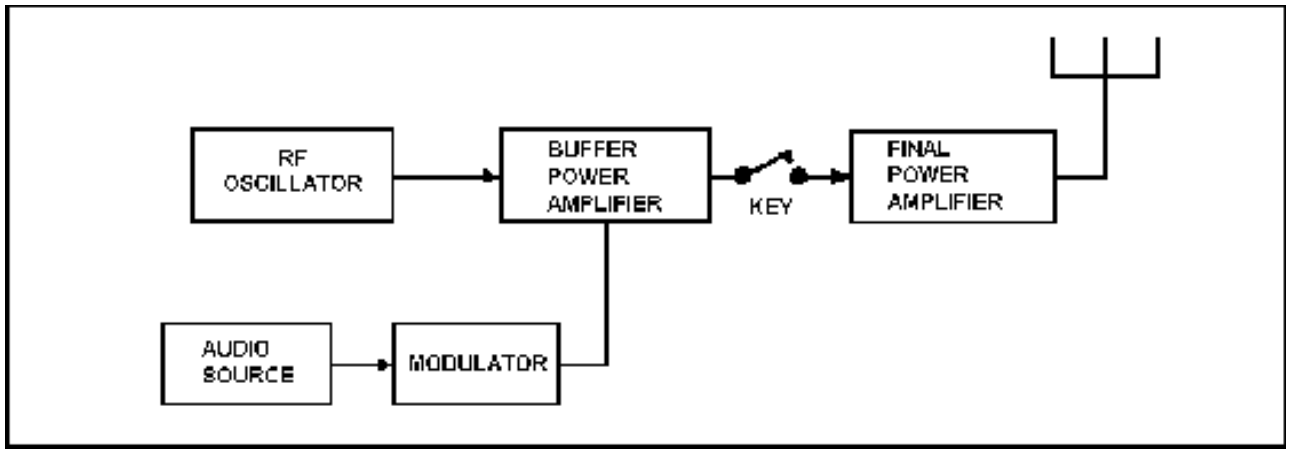

Figure 6-3. Addition of Modulator to Transmitter.

Another method of sending information by way of the transmitter is to use a variable audio source, such as a microphone, to supply the modulator input signal. This system does not require the use of a key. Information is transmitted by combining the microphone's audio voltage with the transmitter's radio frequency; when this combination arrives at the receiver, the audio portion is separated from the radio frequency, amplified, and emitted by the speaker as audible sound that closely imitates the human voice.

DEFINITION OF TERMS

Modulation

The word modulate means to adjust, vary, or regulate. The term amplitude modulation means to regulate or vary the amplitude of the output waveform in a radio-frequency transmitter. Usually, these variations are made to occur at an audio-frequency rate.

Carrier

Carrier is the name given to the radio-frequency wave that is developed by the transmitter's radio-frequency oscillator and transmitted from the antenna. The carrier's job is to carry or transport the intelligence from the transmitter to the receiver. Intelligence can be in the form of code or audio frequencies. The carrier itself does not contain intelligence: it is the transporter of intelligence.

Intelligence

Intelligence is the voice, music, sound, or information that is sent from the transmitter to the receiver. Usually, this intelligence is to be heard by the human ear and, for this reason, the intelligence will be in the audio-frequency range.

METHODS OF MODULATING CARRIER

The audio voltages used to modulate the RF carrier are very weak when they leave the microphone or audio oscillator. For this reason, the audio voltage must be amplified by audio voltage and power amplifiers before it is capable of modulating the RF carrier. These stages of audio amplification are considered to be a part of the modulator. Figure 6-4 shows a typical modulator that could be used regardless of the type of modulating used by the transmitter.

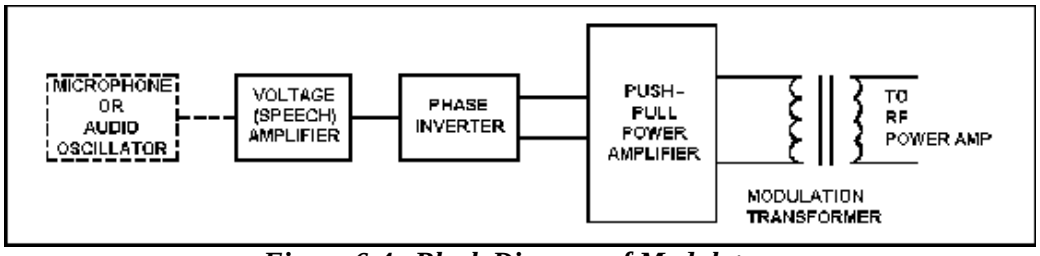

Figure 6-4. Block Diagram of Modulator.

Plate Modulation

In a typical stage of RF amplification (A of figure 6-5), the output waveform has a constant frequency and a constant amplitude. The amplitude of the output waveform shown in A of figure 6-5 was produced with a plate voltage of 500 volts dc. The amplitude of the output wave can be changed in various ways. One way is to vary the plate voltage. In B of figure 6-5, the plate voltage has been increased from 500 to 750 volts dc. Note the resultant increase in output amplitude. In C of figure 6-5, the plate voltage has been reduced to 250 volts dc, which results in a decreased output amplitude. In plate modulation, the audio voltages are fed to the plate of the power amplifier in series with the B+ or plate voltage.

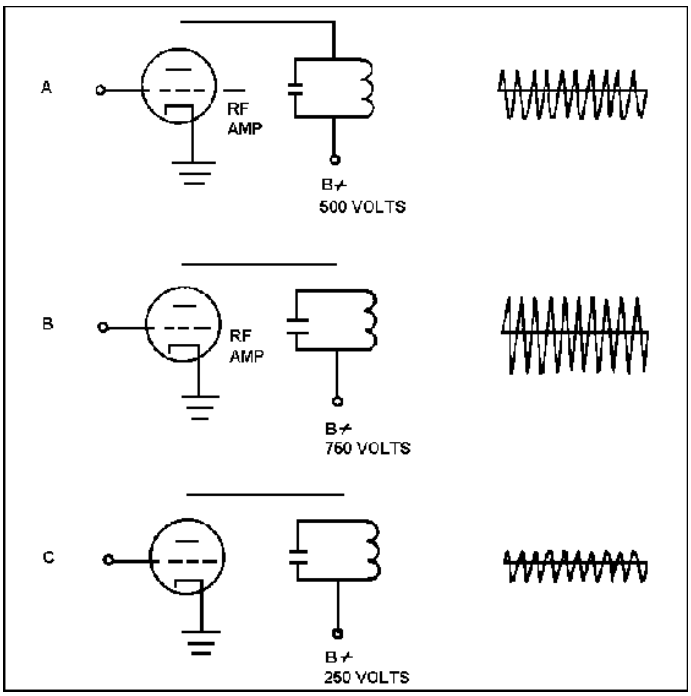

Figure 6-5. Effect of Varying Plate Voltage on Output Amplitude.

Figure 6-6 shows a plate-modulated RF power amplifier. Note in figure 6-6 that the secondary of the modulation transformer is in series with the B+. The audio-modulating voltage is an ac voltage as shown in waveform 2, figure 6-6. This means it is alternately positive and negative. When it is positive, it adds to the B+ and increases the plate voltage on the amplifier tube (waveform 3, figure 6-6). The tube amplifies more as shown in waveform 4, point A. When the audio-modulating voltage is negative (wave 2, point C, figure 6-6), it subtracts from B+ and decreases plate voltage (wave 3, point C, figure 6-6). The amplitude of the RF output waveform rises and falls in direct relationship to the audio-modulating voltage. Note that if a line is drawn connecting the peaks of the RF carrier output wave as shown in figure 6-6, wave 5, the line is a direct representation of the audio-modulating wave. The line is often called the envelope of the modulated wave and is actually the intelligence being carried by the RF carrier. There are circuits in the receiver that can separate this envelope from the carrier, thereby completing the transmission of intelligence from transmitter to receiver. Now consider some values of voltage that are used in figure 6-6. The audio voltage across the secondary of the modulation transformer varies from 0, to +300, to 0, to -300, and back to 0. Since the audio voltage is added in series with the B+ (+500 volts), the plate voltage will vary from 500 volts (B+), to 800, to 500, to 200, and back to 500.

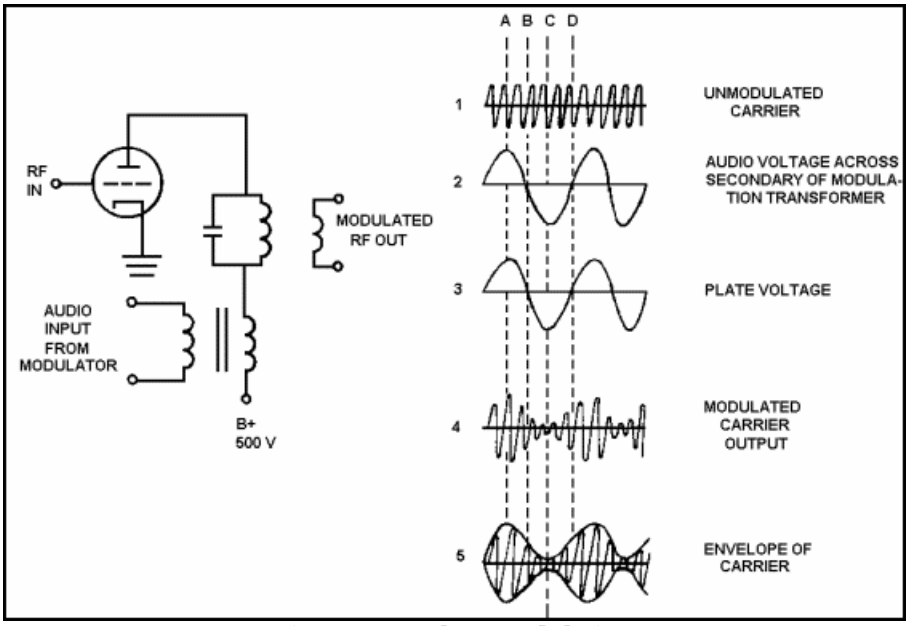

Figure 6-6. Plate Modulation.

Grid Modulation

Practically any element of an RF amplifier tube can be used to modulate the carrier waveform. The choice depends upon circuit conditions and the desire of the circuit designer. For example, if the RF amplifier is a triode tube, the secondary of the modulation transformer can be connected in series with the grid resistor (figure 6-7). Here, the modulating audio voltage is placed in series with and adds to or subtracts from the grid bias voltage, thereby causing the amplitude of the RF output to vary at an audio rate. The big difference between plate modulation and control grid modulation is the relative strength of the audio-modulating voltage required. Plate modulation will normally require several hundred volts of audio, whereas control grid modulation will require only a few volts of audio. In the pentode RF amplifier, the modulation transformer may be connected to the screen grid or the suppressor grid.

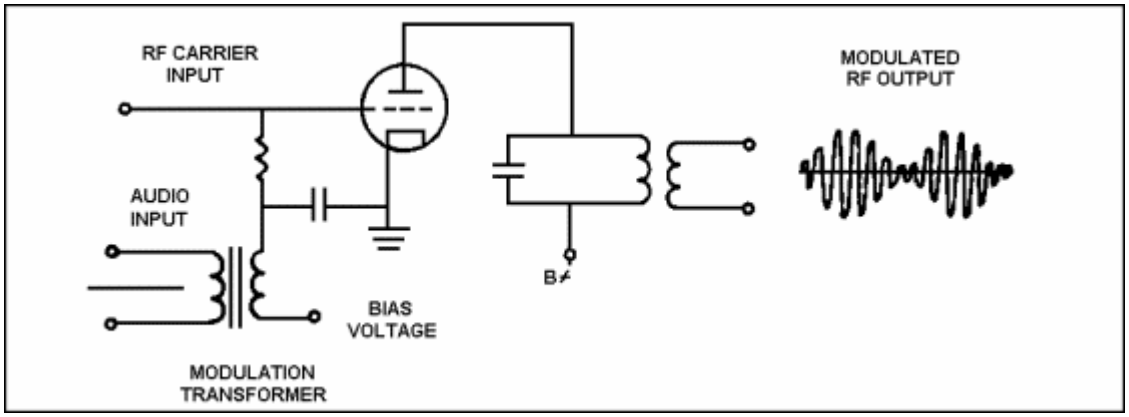

Figure 6-7. Control Grid Modulation.

LEVELS OF MODULATION

The two levels of modulation are high-level and low-level. High-level modulation refers to plate modulation described above. This method is called high-level because it takes place in the final stage of the transmitter, the power amplifier. Control grid modulation is a type of low-level modulation because it can take place at any stage, such as the buffer stage, prior to the final amplifier. High-level modulators have a greater efficiency than low level modulators because in low-level, modulation takes place before the final amplifier. This means that the modulated signal must pass through one or more stages before leaving the transmitter. These stages, in order to amplify the modulated signal, must be class A amplifiers in order to prevent distortion of the intelligence (audio wave). In high-level modulation, there are no stages to follow modulation that could cause distortion. Therefore, the final amplifier can be operated as class C, which has high-plate efficiency. All transmitters are not modulated at the high level because several stages of audio amplification are required to boost the audio voltage to a usable level. For example, most high-wattage transmitters used by the Signal Corps do use high-level plate modulation, but the choice is mainly up to the individual designer.

SIDEBANDS

When any two different frequencies are added or mixed together, two new frequencies are produced. One of the new frequencies is the sum of the original frequencies and the other new frequency is the difference between the original frequencies. As an example, assume that we are broadcasting from radio station WOR in New York that has a carrier frequency of 710,000 hertz. If we strike a note on a piano (256 hertz), this frequency is picked up by a microphone, amplified, and used to modulate the carrier. In the process of modulation, 256 hertz are mixed with 710,000 hertz. Two new frequencies are generated, the sum frequency, 710,256 hertz, and the difference frequency, 709,744 hertz (figure 6-8). These new frequencies are called upper and lower sidebands, respectively. The range of frequencies, from the lowest sideband to the highest sideband, is known as the bandwidth of transmission. The entire bandwidth must be transmitted because most of the radio tones, in addition to some of the transmitted power, are carried by the sidebands. Since all AM broadcast stations must transmit audio frequencies as high as 5,000 hertz, their bandwidth must be at least 10,000 hertz (10 kHz).

PERCENTAGE OF MODULATION

Percentage of modulation is a measure of the extent to which the RF carrier has been modulated. There are three main reasons for monitoring or controlling the percentage of modulation. The first is to modulate the carrier as much as possible because the modulated carrier is more powerful than the unmodulated carrier; the second is to avoid overmodulation since this causes blank spots (gaps) in the carrier with a resultant loss of intelligence. Third, when the final amplifier is overmodulated, the plate conducts heavily for a period of time and then stops conducting abruptly. This sudden application of power and removal of power in the plate tank circuit cause undesirable harmonics and distortion.

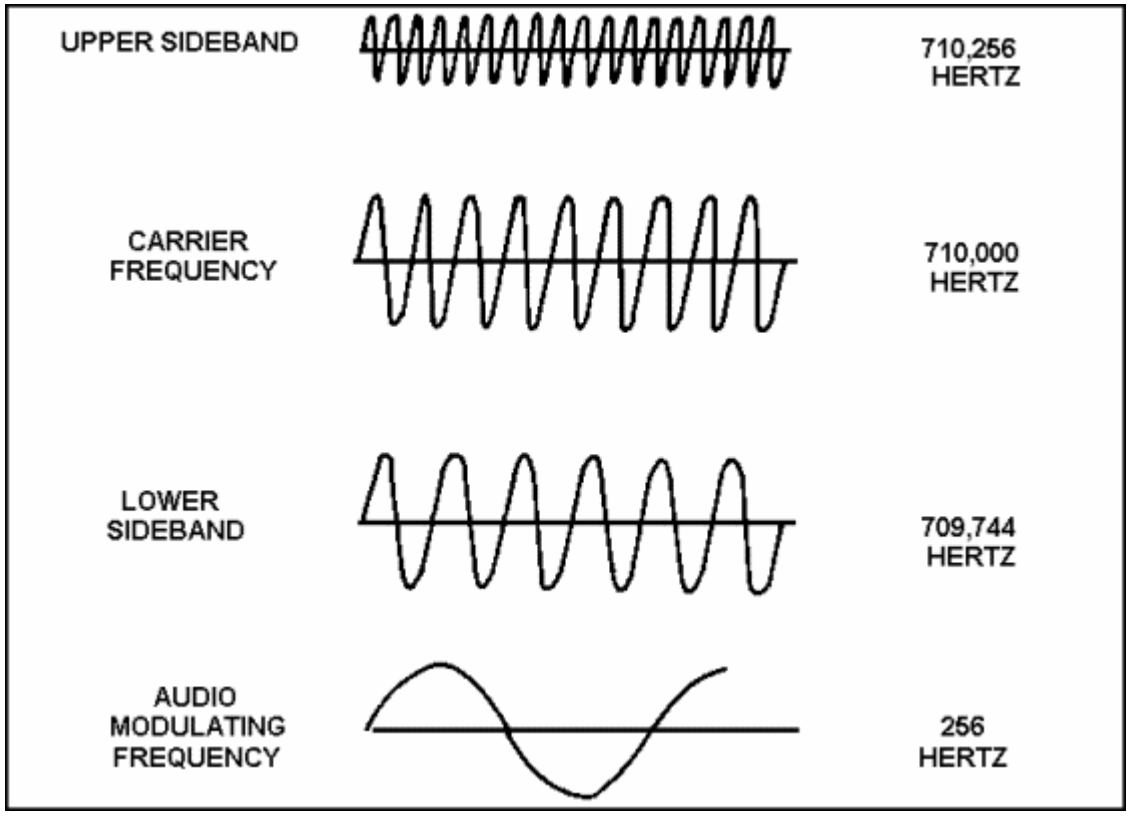

Figure 6-8. Sidebands Created by Modulating Carrier With One Audio Frequency.

100-percent Modulation

The most desirable level of modulation is 100-percent modulation (figure 6-9). This occurs when the amplitude of the modulated wave is twice the amplitude of the unmodulated carrier. If the modulated waveform is less than twice the unmodulated carrier, the output is less than 100-percent modulated. The formula for determining the percentage of modulation is:

$$\% \text{ Mod} = \frac{E \text{ max} - E \text{ carrier}}{E \text{ carrier}} \times 100$$

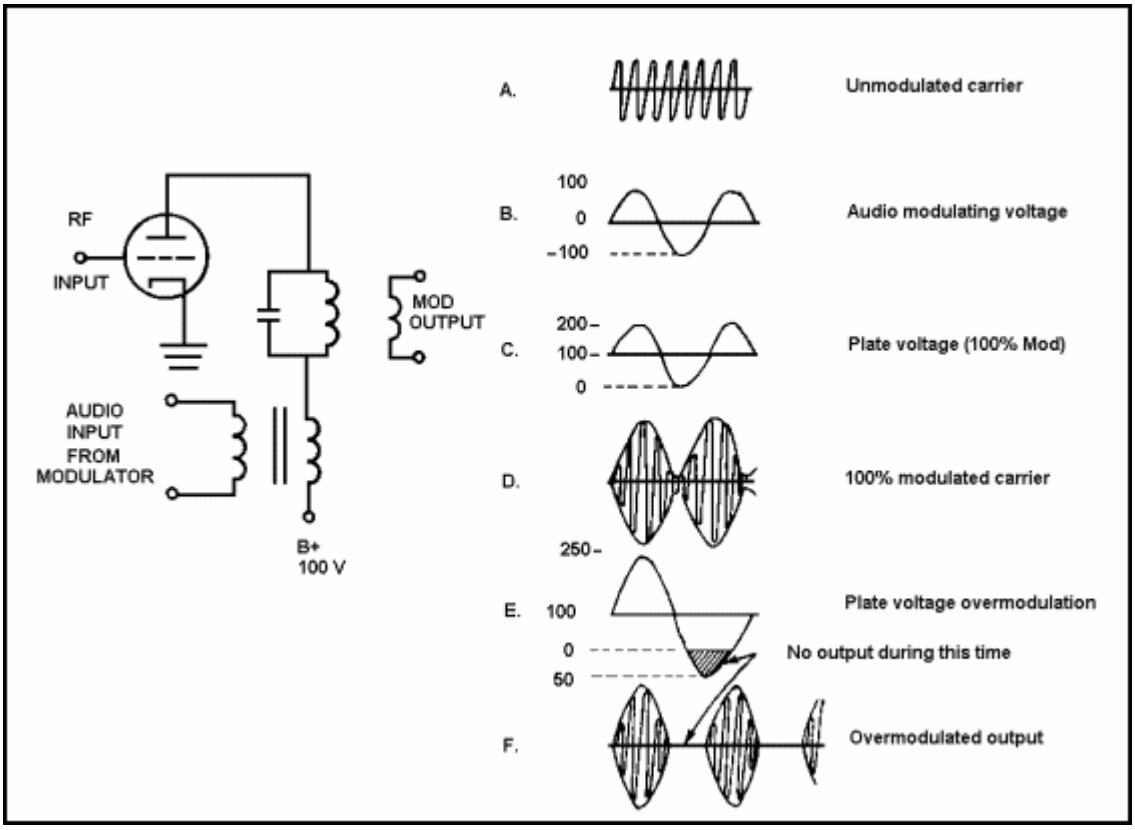

Figure 6-9. 100-Percent Modulation and Overmodulation.

Figure 6-9 shows a plate-modulated power amplifier that has been modulated 100 percent. Waveform A (figure 6-9) shows the waveform of the unmodulated carrier. Waveform B shows the audio-modulating voltage developed in the secondary of the modulating transformer. This audio voltage varies from 0 to +100, to 0, to -100, and to 0. Waveform C describes the plate voltage resulting from the addition of the regular B+ (100 V) and the audio voltage. Waveform D represents the 100-percent modulated carrier with envelope. Most large commercial transmitters have a modulation at all times. Although 100-percent modulation is the most desirable level of modulation, most transmitters operate slightly below this level because 100-percent modulation is almost at the point of overmodulation, which is undesirable.

Overmodulation

The transmitter is said to be overmodulated when the modulated carrier amplitude exceeds twice the unmodulated carrier amplitude. For example, in waveform E (figure 6-9), the plate voltage varies on the positive alternation from 100 volts (unmodulated value) up to 250 volts and then back down to 100 volts. On the negative alternation, the plate voltage varies from 100 volts, down through 0 to -50 volts, and then back up to 100 volts. Note that during the positive alternation, the plate voltage exceeds double the unmodulated value, which is an indication of overmodulation. On the negative alternation, the plate voltage goes down through 0 to -50 volts and cuts off the amplifier tube for the period of time that the plate voltage is below 0 volts (waveform F, figure 6-9). Whenever plate current in a final amplifier is interrupted, new frequencies and harmonics are created. Their number and intensity vary with the degree of overmodulation. These harmonics produce additional sidebands that extend far beyond the normal bandwidth and cause interference with stations operating on slightly higher or slightly lower frequencies. Overmodulation can also cause serious damage to transmitters that are not designed to handle the sudden surges of power.

Distribution of Power in a Modulated Wave

The power in an amplitude-modulated wave is carried by both the RF carrier and the sidebands. The carrier power is relatively constant (except in cases of overmodulation); therefore, the sideband power is the main difference between unmodulated carrier power and modulated power.

When a carrier is modulated by a constant amplitude and constant frequency audio wave, the total modulated output power is found by the following formula:

$$P_{mod}\left(1+\frac{m^2}{2}\right) \times P_{unmod\ carrier}$$

where m = % modulation

As an example to show the amount of power carried by sidebands, assume that a transmitter has an output of 500 watts of unmodulated power. When the transmitter is modulated 100 percent, the modulated power becomes

$$P_{mod}\left(1+\frac{(1)^2}{2}\right) 500 = 500 + \frac{500}{2} = 750 \text{ watts}$$

Of this total, 500 watts are in the carrier and 250 watts are in the sidebands, or the sidebands contain 33.3 percent of the total power. Each sideband contains 125 watts or 16.6 percent of the total power. The available sideband power takes a decided drop when modulation is decreased below 100 percent. For example, if the 500-watt transmitter mentioned above were modulated only 50 percent, the total modulated power output would be only 562.5 watts. Each sideband would contain only one fourth as much power as was obtained by 100-percent modulation. Reducing the modulation from 100 percent to 50 percent causes a 75-percent reduction in sideband power output. Since most of the intelligence and a lot of the power is contained in the sidebands, the desirability of a high percentage of modulation becomes evident.

DISADVANTAGES OF AMPLITUDE MODULATION

Amplitude modulation has only one serious disadvantage. When the receiver is picking up the modulated wave, any atmospheric disturbances (such as lightning) and any man-made disturbance (such as electric motors and ignition noise) are also picked up by the antenna. Most of these noises are audible and unwanted; however, they ride into the receiver on top of the carrier along with the modulating audio. Many times the noise is so strong that it completely overrides and covers up a weak station, making reception impossible or at least unpleasant. Frequency modulation was developed to overcome this serious defect.

REVIEW EXERCISES

Circle the letter to the correct answer to each question.

1. What radar system normally employs a modulator?

   a. Receiver.
   b. Antenna.
   c. Transmitter.
   d. Indicator.

2. What is the function of a buffer amplifier?

   a. To generate the audio signal.
   b. To generate the radio-frequency carrier.
   c. To prevent the oscillator from overloading the final power amplifier.
   d. To prevent the final power amplifier from overloading the oscillator.

3. What best describes amplitude modulation?

   a. Varying the audio amplitude at a carrier rate.
   b. Varying the carrier amplitude at an audio rate.
   c. Varying the amplitude of the audio according to the changes in carrier frequency.
   d. Varying the frequency of the carrier according to the amplitude changes of the audio.

4. Which formula is used to compute the percentage of modulation?

   a. $\%\ \text{Mod} = \frac{E_{max} - E_{carrier}}{E_{carrier}} \times 100$

   b. $\%\ \text{Mod} = \frac{E_{min} - E_{carrier}}{E_{carrier}} \times 100$

   c. $\%\ \text{Mod} = \frac{E_{max} - E_{carrier}}{E_{min}} \times 100$

   d. $\%\ \text{Mod} = \frac{E_{min} - E_{carrier}}{E_{max}} \times 100$

5. What class of amplifier is used for low-level modulation?

   a. Class A.
   b. Class AB.
   c. Class B.
   d. Class C.

6. High-level modulation is performed in what circuit?

   a. Final IF amplifier.
   b. Final AF amplifier.
   c. Final power amplifier.
   d. Final speech amplifier.

7. What percentage of the total transmitted power is contained in the sidebands if a transmitter is modulated 100 percent?

   a. 25 percent.
   b. 33.3 percent.
   c. 50 percent.
   d. 75.5 percent.

8. How many sidebands are produced if a radio frequency is modulated by a single audio frequency?

   a. 1.
   b. 2.
   c. 3.
   d. 4.

9. What produces overmodulation?

   a. Excessive audio voltage.
   b. Excessive audio frequency.
   c. Excessive radio frequency.
   d. Excessive RF voltage.

10 What is a disadvantage of amplitude modulation?
.

   a. High cost of production.
   b. High-radiation losses.
   c. Excessive overmodulation.
   d Excessive noise interference.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

Lesson 7

SUPERHETERODYNE RECEIVERS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to describe the purpose, functions, and uses of superheterodyne circuits, to include converters, local oscillators, intermediate-frequency amplifiers, detectors, audio-frequency amplifiers, and automatic volume control.

Conditions. You will have this subcourse book and will work without supervision.

Standard. You must score at least 75 on the end-of-subcourse examination that covers this lesson and lessons 1 through 6.

DEVELOPMENT OF SUPERHETERODYNE RECEIVER

The two basic types of receivers are the tuned radio frequency (TRF) and the superheterodyne (superhet). In TRF receivers, radio frequency (RF) amplification takes place at the frequency of the incoming RF signal, and all tuned circuits are adjusted to this frequency. The superhet receiver differs essentially from the TRF receiver in that it changes the frequency of the received signal to a fixed vale at which the tuned amplifying circuits can operate with maximum stability, selectivity, and sensitivity. The conversion of the received signal frequency into a lower intermediate frequency (IF) in the superhet receiver is based on the heterodyne effect.

The TRF receiver is the forerunner of the superhet and suffers from several disadvantages inherent in its operation. Since all its RF stages function at the same frequency, stray coupling between output and input circuits may provide sufficient feedback to cause instability or oscillation. Furthermore, it is difficult to achieve uniform amplification of the RF stages over the entire frequency range of the receiver. At the higher frequencies, the gain of each stage tends to fall off and, therefore, the sensitivity of the receiver is reduced. Finally, the most serious drawback of the TRF receiver is that the selectivity of the tuned circuits cannot be kept uniform over the frequency range. At the high-frequency end of the tuning range, the selectivity of the TRF receiver decreases markedly. This lack of selectivity can become serious at the higher frequencies generally used in electronic communication systems.

The superhet was developed to overcome the deficiencies inherent in the TRF. The major improvement offered by the superhet is that all incoming frequencies are converted to a single intermediate frequency. This frequency usually has a value below the carrier frequency of the incoming signal. Regardless of the value of the received signal frequency, the signal with its audio modulation is always converted to this fixed intermediate frequency.

Then it can be amplified to the desired degree in a fixed-frequency IF amplifier. This amplifier can be designed to have higher and more uniform amplification and selectivity per stage over the tuning range of the receiver than is possible with a variable frequency amplifier.

At the lower frequency of the IF amplifier, it is possible to obtain more amplification than in the TRF amplifier without the TRF difficulties of feedback and oscillation. Furthermore, the selectivity of an IF amplifier is considerably greater than that of an RF amplifier operating in higher signal frequencies. In summation, the superhet receiver is superior to the TRF receiver because it is more selective and has higher gain per stage and uniform selectivity and sensitivity. In addition to these advantages, it has fewer variable-tuned circuits and is more easily adapted to multiband reception.

For these reasons, superheterodynes have replaced TRF receivers in practically all applications.

BEAT FREQUENCIES

The production of beat frequencies can best be understood by first considering a similar effect with sound waves. When two notes that are close in pitch (frequency) are sounded at the same time, a throbbing or pulsating sound is heard. These pulsations, or beats, occur at a frequency equal to the frequency difference between the two notes and are caused by interference between their sound waves. This effect is often observed when two notes in the lower registers of a pipe organ are sounded together or when two tuning forks that differ slightly in pitch are struck.

The production of a beat note is illustrated in figure 7-1. Assume that two tuning forks are struck at the same time, one with a pitch of 90 hertz, as shown in A of figure 7-1, and the other with a pitch of 100 hertz, as shownin B of figure 7-1. These two tones are represented graphically by sine waves: 9 cycles of the 90-hertz tuning fork and 10 cycles of the 100-hertz fork are given. It is found that the two sound waves interact with each other. Sometimes they are vibrating together (in phase); at other times, they are completely opposed to each other (out of phase). Whenever the two waves are in phase with each other, their amplitudes add together and the sound waves reinforce each other.

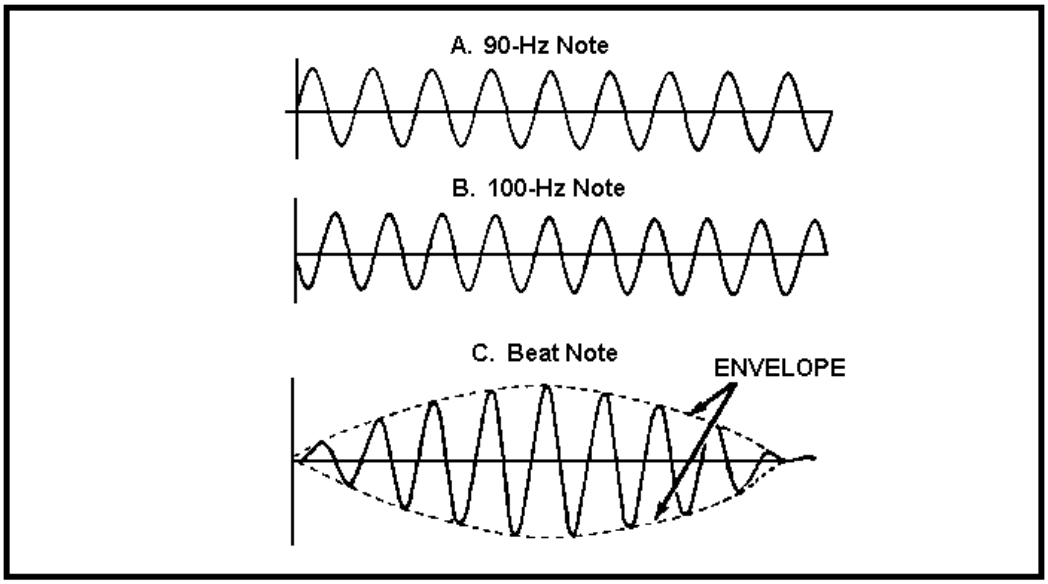

Figure 7-1. Production of Beat Frequency.

Figure 7-1. Production of Beat Frequency.

At the points where the waves are out of phase, they subtract from each other. In between these two extremes the waves reinforce or interfere with each other in varying degrees. This is clearly visible in part C of figure 7-1. Here, the amplitudes of the two tones have been added algebraically to obtain the resultant waveform. Initially, the two notes are in opposition and their resultant amplitude is zero. After approximately 5 cycles have passed, the forks vibrate in phase, and the resultant amplitude is the addition of the amplitudes of both waves. After approximately 10 cycles, the two notes are again out of phase and the resultant amplitude is zero.

As a result of this alternate reinforcement and interference, the two notes will at times swell in volume and at other times they will be almost inaudible, thus producing beats. As seen in figure 7-1, this beat frequency is equal to the difference between the two tones. One cycle of the beat note is indicated in C of figure 7-1 by the contour or envelope connecting the peaks of the resultant wave. Actually, with the 90-hertz and 100-hertz tuning forks, a beat frequency equal to the difference, or 10 hertz, is obtained.

The principle of beats also applies to alternating currents of different frequency. Two alternating currents can be combined in such a manner as to produce a beat or difference frequency between them. If the beat frequency is within the range of hearing (approximately 20 to 20,000 hertz) it can be made audible by transforming it to sound waves. As an example, assume that an unmodulated 1,000-kHz radio wave is received in a radio set and that this signal is mixed with the output of an oscillator operating at a frequency of 1,001 kHz. In figure 7-2, the RF signal is at A and the oscillator frequency is at B. The resultant waveform is shown at C. It is generated by alternate reinforcement and cancellation as in the case of the two sound waves. The beat note, which is 1,001 kHz - 1,000 kHz = 1 kHz, or 1,000 hertz, is represented by the envelope of the resultant signal. If this signal is rectified as in D and the RF pulses are filtered out, only the 1,000-hertz beat note remains, as in E. The electrical beat frequency, then, is passed through a loudspeaker or headphone and becomes audible as a 1,000-hertz tone. In principle, this is the process that takes place when a CW signal is received by a superhet receiver.

The reception of a modulated RF signal in a superheterodyne receiver takes place essentially in the manner described above. A of figure 7-3 shows a typical modulated RF signal intercepted by the receiver antenna. It is amplified to a useful level with an RF amplifier. In B of figure 7-3, it is mixed with the output of a local oscillator that is a continuous wave of a frequency different from the incoming signal frequency by an amount equal to the desired difference, or intermediate, frequency. It does not matter whether the frequency of the local oscillator is higher or lower than the RF signal frequency as long as the difference between the two is equal to the correct intermediate frequency.

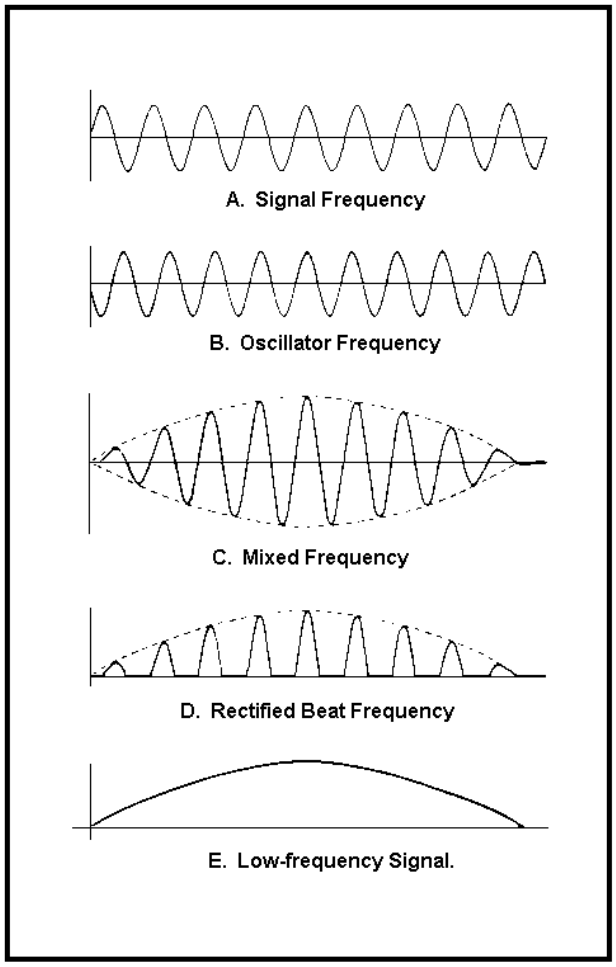

Figure 7-2. Superheterodyne Reception of Unmodulated (CW) Signal.

Figure 7-2. Superheterodyne reception of Unmodulated (CW) Signal.

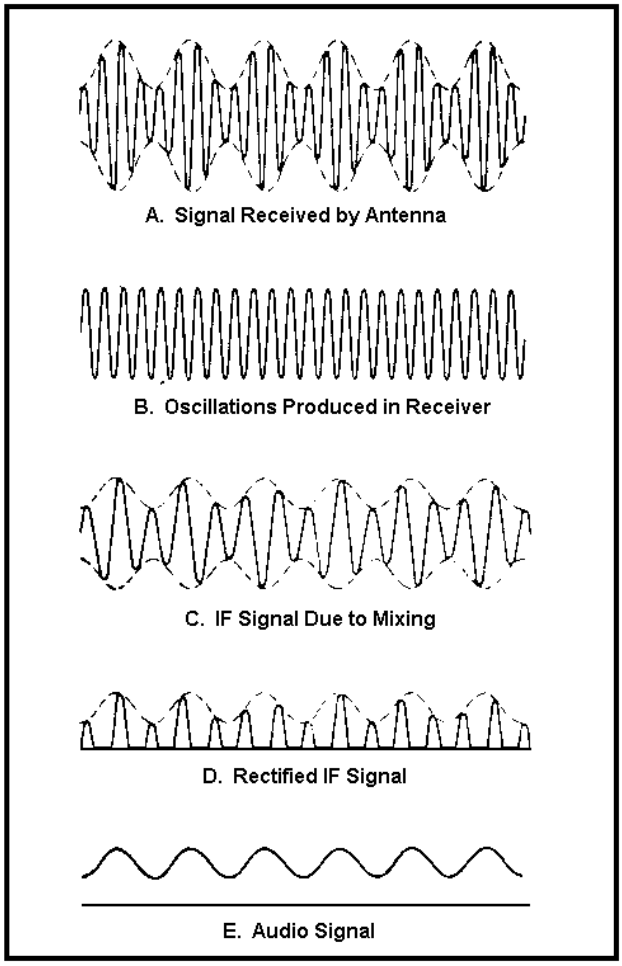
A. Signal Received by Antenna
B. Oscillations Produced in Receiver
C. IF Signal Due to Mixing
D. Rectified IF Signal
E. Audio Signal

Figure 7-3. Superheterodyne Reception of Modulated RF Signal.

Figure 7-3. Superheterodyne Reception of Modulated RF Signal.

For example, if the frequency of the incoming signal is 1,500 kHz and the desired intermediate frequency is 455 kHz (a common value), then the frequency of the local oscillator can be either 1,500 + 455 = 1,955 kHz, or 1,500 - 455 = 1,045 kHz. In either case, an IF equal to the difference of 455 kHz is produced. IF always is chosen well above the highest audio-frequency component in the desired signal; otherwise, considerable distortion of the desired intelligence would result. The result of mixing the modulated RF signal with the output of the local oscillator is shown in C of figure 7-3. An intermediate difference, or beat, frequency is generated as before. The amplitude of the beats, however, varies in this case as the amplitude of the modulated wave. In other words, the envelope of the IF signal produces the modulation of the received RF signal.

The higher frequency-modulated radio signal has been converted into a lower frequency signal that carries the original modulation. The stage of the receiver that accomplishes this conversion is known as the mixer or first

detector. The modulated IF signal then can be amplified to the required level by one or more stages of IF amplification. It is then rectified and filtered in a detector, sometimes called the second detector, that leaves only the audio modulation (D and E of figure 7-3). This audio signal is then amplified and applied to a speaker or headphones.

BASIC STAGES OF SUPERHETERODYNE RECEIVER

Figure 7-4 shows a block diagram of a superheterodyne receiver. The basic stages are an antenna stage for intercepting the signals from a transmitter; a variable-tuned RF amplifier stage for selecting the desired signal (the RF amplifier is not absolutely essential for superheterodyne reception, but its presence improves the signal-to-noise ratio and adds other desirable characteristics that will be discussed); a mixer in which the RF signal is combined with the output of a local oscillator to generate an IF signal; a local oscillator for generating the signal that beats with the RF signal (this can be any one of the conventional oscillators discussed in lesson 5); an IF amplifier section consisting of one or more stages for amplifying the IF signal from the mixer; a detector circuit for demodulating the IF signal; an audio-frequency power amplifier consisting of one or more stages for amplifying the audiofrequency output of the detector to a value sufficient to drive a loudspeaker or headphones; and a loudspeaker or headphones for converting the electrical F variations into sound waves corresponding to the original audio energy that modulates the RF signal at the transmitter.

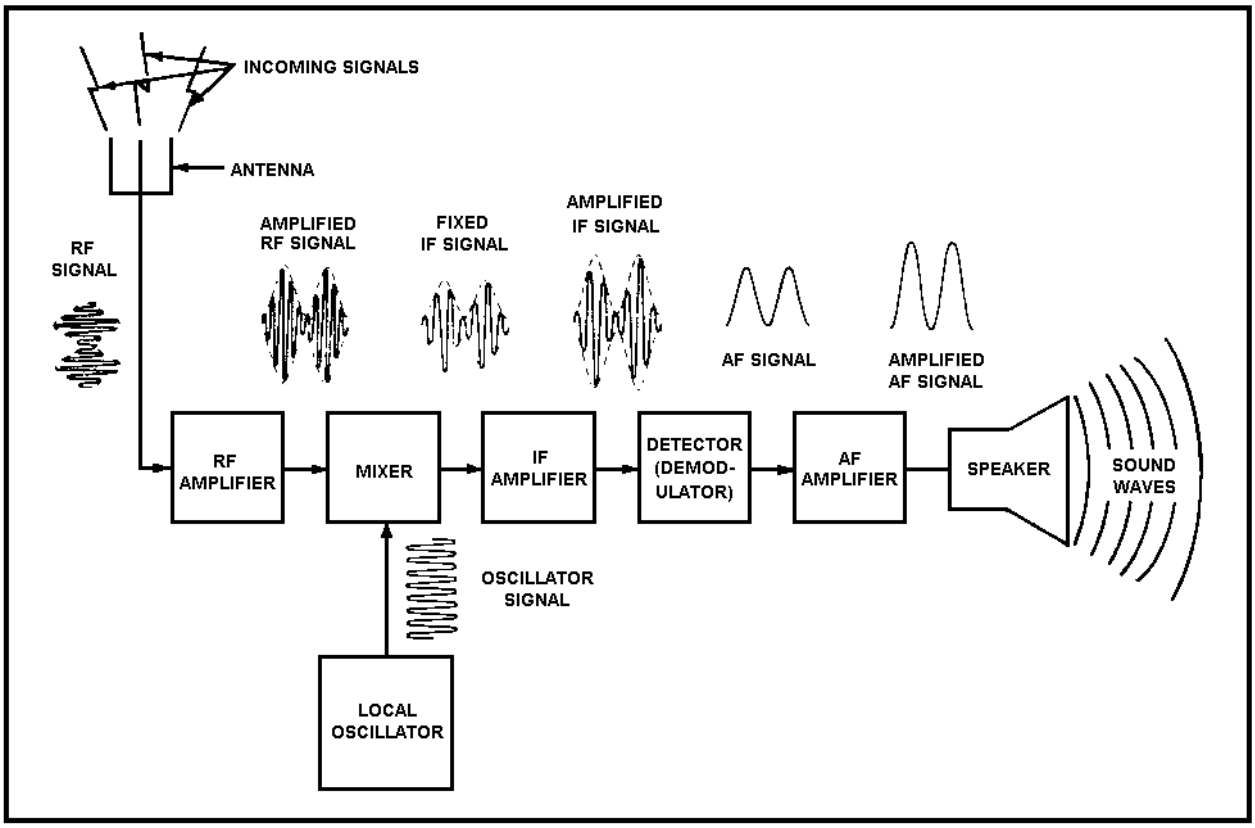

Figure 7-4. Block Diagram of Basic Superheterodyne Receiver.

Figure 7-4. Block Diagram of Basic Superheterodyne Receiver.

The fundamental operation of the superheterodyne receiver for the reception of AM signals is as follows (figure 7-4). Modulated RF signals from an infinite number of transmitters are intercepted by an antenna. They are coupled through an antenna input transformer to the first stage of the receiver, usually a variable-tuned RF amplifier. The desired RF signal is selected by the tuned circuit of the RF amplifier. This signal is amplified and all other signals are rejected to some degree.

The amplified RF signal is coupled to the input of the mixer stage where it is combined with the output of the local oscillator. In this process of heterodyning, a beat frequency equal to the difference between the RF signal and local oscillator frequencies is produced. The frequency of the local oscillations is chosen either above or below (usually above) the RF signal frequency by the required amount so that the difference frequency is desired IF. The resulting IF signal contains the same modulation as the original RF signal.

The IF signal is amplified in a fixed-tuned IF amplifier stage and is coupled to the input of the detector. The detector stage removes the audio modulation contained in the IF signal and filters out the IF carrier, which is no longer needed. The resulting audio signal is amplified to the level required for energizing an electromechanical reproducer. The electrical audio variations are converted into the corresponding sound waves by the reproducer (loudspeaker or headphones).

Radio-frequency Amplifier Stage

The basic superhet receiver will operate without a separate RF amplifier simply by connecting the antenna to the mixer stage. However, one or two tuned RF stages ahead of the frequency converter are used almost always in modern superhet receivers since several important advantages can be attained with an RF amplifier: suppression of image interference, improvement in selectivity, improvement in signal-to-noise ratio, and isolation between the antenna and frequency converter (radiation suppression). The addition of the RF amplifier also improves the gain of the receiver, but this is not its primary function, since gain is more efficiently obtained in the IF amplifier.

Frequency Conversion Stage

Methods. The oscillator and mixer circuits together achieve the frequency conversion of the RF signal to an intermediate frequency. Various methods and circuits exist for accomplishing this. All these arrangements are similar in that they use the nonlinear characteristic of a vacuum tube for mixing the RF signal and local oscillator frequencies. The plate current of the mixer tube is varied to produce a voltage of the desired IF across the primary of a tuned IF transformer. The secondary of this transformer is coupled to the grid of the first IF amplifier stage. The methods for frequency conversion differ chiefly in the types of tubes used and in the manner in which the signal and oscillator voltages are injected into the mixer tubes.

Two methods are used to produce the desired frequency conversion. In one, a separate oscillator tube (usually a triode) is used to produce the local oscillations. The output of this tube is injected into another tube by some means of coupling. The incoming RF signal also is injected into this second tube along with the local oscillations. The two signals can be injected into the second tube at the same point or at different points, where they combine to produce the IF (among others) in the output. The tube in which the two signals are combined is called the mixer. The distinguishing feature of this method is that two separate tubes are used.

In the second method only one tube, known as a converter, is used. The oscillator and mixer tubes are combined into a single tube that performs both functions. In the usual arrangement, the RF signal is injected at one electrode, the local oscillator signal's being injected at some other electrode. There are also converter tube types in which both signals are injected at the same electrode. The advantage of this method is that only one tube is necessary.

Basic Converter. Before the development of modern pentagrid converters, separate mixers and oscillators were used universally. The mixer tube (figure 7-5) functions as an ordinary plate detector biased approximately to cutoff. The tank circuit at the input of the mixer is tuned to the frequency of the incoming RF signal. The oscillator grid tank circuit is tuned above (or below) the RF signal frequency by an amount equal to the intermediate frequency. The IF transformer in the place circuit of the mixer is tuned to the desired difference frequency. The oscillator and mixer tuning capacitors are ganged together to permit single-control tuning.

A conventional tickler feedback oscillator is used in this frequency converter circuit. Any other type also can be used as a local oscillator. For a properly designed mixer, very little power is drawn from the local oscillator. Oscillations from the plate circuit of the oscillator are coupled to the grid of the mixer by means of a coupling capacitor, a method known as grid injection. The oscillator voltage applied to the grid of the mixer tube should be as large as possible for maximum conversion gain. However, to avoid overloading, the sum of the oscillator and signal voltages impressed on the mixer grid should not exceed the grid bias. If the mixer is overloaded by driving the grid positive, both the gain and the input selectivity of the stage are reduced.

Mixer Characteristics. It is a fundamental fact that a device with a linear characteristic produces no interaction between currents of different frequency and, therefore, no beat frequencies. Mathematical analysis showsthat a nonlinear voltage current characteristic leads to production of new frequencies in the output that are not present in the input. If two alternating currents of different frequency are impressed on a nonlinear device, they interact to produce a beat or difference frequency in the output. This is not the only additional frequency produced in the output of a nonlinear device. Recall the generation of sum and difference frequencies in the lesson on modulation. For example, if the output current of a device varies as the square of the applied voltage, the following prominent frequencies are produced as a result of applying two sine waves at different frequencies: the original frequencies of the applied alternating currents, a frequency equal to the sum of the original applied frequencies, and a frequency equal to the difference of the two applied frequencies.

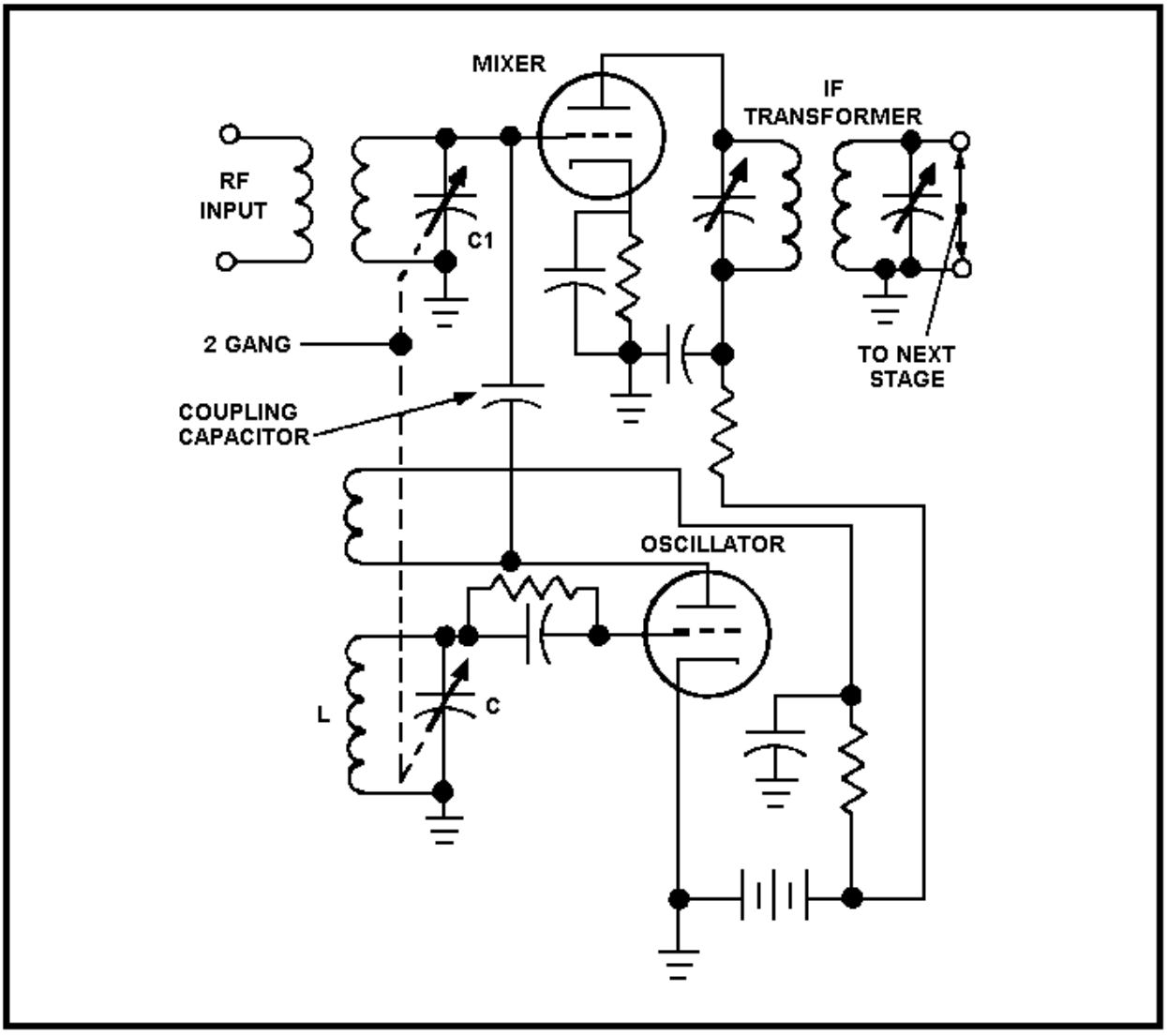

Figure 7-5. Triode Oscillator and Triode Mixer.

Figure 7-5. Triode Oscillator and Triode Mixer.

If the nonlinear device follows a more complex relationship between input and output, many additional frequencies also will be present in the output. For superheterodyne reception, only the sum or difference frequency is of interest, and all other frequencies in the output of the mixer must be filtered out. Many devices have a nonlinear voltage current characteristic. One of the simplest is the ordinary vacuum tube when operated along the curved part of its characteristic curve.

The simple plate detector type of mixer performs very well and has the advantage of low cost. Its almost universal use in the early days of superhet radios led to the name "first detector" for the mixer stage, a name still used occasionally to describe other types of mixers. Mixers using triodes and pentodes are characterized by high-conversion gain and good signal-to-noise ratio. Their relatively low-noise level makes them suitable for use at high frequencies. The chief disadvantage of triode and pentode converter circuits is the undesirable interaction caused by coupling between the mixer and oscillator portions. A strong interfering signal at the

mixer input, whose frequency is close to the oscillator frequency, tends to make the oscillator synchronize, or lock in, with the interference, producing frequency instability. Pulling is especially annoying at higher frequencies where the local oscillator and signal frequencies differ by only a small percentage. The desire to isolate the local oscillator and RF signal input circuits from each other led to the development of pentagrid mixer and converter tubes.

Intermediate-frequency Amplifier Stage

The IF amplifier is of special importance in superhet receivers because it controls, to a major extent, the selectivity and gain of the complete receiver. The amplifier contains from one to three tuned stages and utilizes high-gain pentode tubes in each stage. Operating only at the IF frequency, the tuned circuits of the amplifier can be adjusted permanently for optimum amplification and selectivity. No variable tuning or tracking problems are met in the IF amplifier.

In addition to providing high gain and sufficient selectivity between adjacent channels, the IF amplifier must have the required fidelity to preserve intact the intelligence superimposed on the carrier at the transmitter. Amplitude modulation of a carrier generates sideband frequencies numerically equal to the carrier frequency, plus and minus the highest modulation frequency present. For example, if modulation containing audio frequencies up to 5,000 hertz is to be reproduced faithfully, the receiver must be capable of amplifying equally all frequencies in a band from 5,000 hertz below the carrier (lower sideband) to 5,000 hertz above the carrier (upper sideband). This means that the IF amplifier must pass uniformly a band of frequencies 10 kHz wide.

The design of the tuned circuits in the IF amplifier determines the bandpass characteristics. The tuning or selectivity of the IF transformers must not be so sharp as to cut a portion of the lower and upper sidebands containing the modulation. A 10-kHz bandwidth generally is considered sufficient for reasonably faithful reproduction of speech and music. Narrower bandwidths often are used for military communications where a compromise between intelligibility and rejection interference signals and noise is desired.

Detector Stage

Most superhet receivers utilize a diode detector for rectification of the modulated signal. Because of the linear characteristic between the modulated RF input voltage and the rectified output current, a diode is capable of handling high-level signals with little distortion. It is, therefore, well adapted for use after the high-gain IF stages of a superhet receiver where the more sensitive grid-leak detector and the plate detectors would be overloaded. Therefore, diode detectors are preferred over other detectors in superhet receivers.

The diode detector has no gain, however, so there is a loss of signal strength. To make up for this loss, the diode detector rarely is used alone, but is combined with an audio amplifier in the same stage. As will be seen later, the use of dual-function tubes (diode-triodes and diode-pentodes) makes this a comparatively simple matter. The gain of the combined detector-amplifier stage is then comparable to that provided by other types of detectors.

More serious is the comparatively large current the diode detector draws from its tuned input circuit. This current damps out the resonant peak of the tuned circuit, substantially reducing the selectivity of the stage. This loss in selectivity must be compensated for by having a sufficient number of tuned stages in the receiver to make the overall selectivity satisfactory. In receivers with a separate tuned RF amplifier and two IF stages, the selectivity is sufficient.

Audio Amplification Stage

After the modulation has been extracted from an incoming signal, a relatively weak audio voltage is made available at the output of the detector. In practically all cases, this audio signal first must be strengthened by one or two stages of audio amplification before it is capable of energizing a pair of headphones or a loudspeaker. It is the function of the audio amplifier to raise the audio voltage from the detector to a comfortable listening level with a minimum of distortion. The amount of audio amplification needed depends on the power requirements of the reproducer. One stage of audio amplification generally is sufficient to operate a headset or a small loudspeaker. A larger loudspeaker, however, requires a powerful audio amplifier consisting of several stages.

Sound Reproduction Stage

The AF output contains, in electrical form, the original modulation superimposed on the carrier at the transmitter. It is the function of the reproducer to convert the AF current variations in the output stage of a receiver into audible energy corresponding to the sounds originally spoken into the transmitter microphone. Reproducers are electromechanical devices that translate the current variations at their input into corresponding mechanical vibrations at the output. These mechanical vibrations, in turn, generate the airpressure variations that produce the sensation of sound.

The loudspeaker must transform electric currents in the audio-frequency range into the corresponding sound waves. Sound waves are radiated best if the loudspeaker makes contact with a large surface of air surrounding it. For this purpose, the electromechanical driving mechanism of a loudspeaker is coupled mechanically to fairly large cones, or horns, capable of pushing large amounts of air in front of them. However, even with efficient designs, these loudspeakers produce considerable frequency and harmonic distortion of the AF waveform. Harmonic distortion of the waveform occurs because the complicated loudspeaker driving mechanism cannot be made to act in a strictly linear manner. As in detectors, nonlinear operation introduces new (harmonically related) frequencies into the output that were not present in the input.

SCHEMATIC REPRESENTATION OF SUPERHETERODYNE RECEIVER

Figure 7-6 shows a schematic for a typical eight-tube superheterodyne receiver consisting of one stage of IF amplification, a combined detector, automatic volume control (AVC), a first AF amplifier stage, and a push-pull power amplifier stage. The receiver is operated from the 110-volt ac line through a full-wave rectifier power supply and filter circuit. The power supply provides both the high-voltage dc for the plates and screengrids, and the low-voltage dc for the heaters of the vacuum tubes.

Antenna Input and RF Amplifier

A signal intercepted by the receiver antenna is coupled to the grid of the RF amplifier tube, V1, through the RF input transformer, T1. The grid-input circuit of the tube is tuned to the desired signal with a tank circuit consisting of the secondary of T1 and variable capacitors. The selected signal then is amplified by V1 and fed to the mixer stage through the RF coupling transformer, T2. An AVC voltage is applied to the grid of V1 through R1.

Local Oscillator

The local oscillator, consisting of V7 and associated circuits, generates oscillations higher than the RF carrier frequency by an amount equal to the IF(456 kHz). For this purpose a conventional Hartley oscillator is used, and its output from the grid of triode oscillator tube V7 is coupled through C22 to grid 3 of the pentagrid mixer tube, V2. The oscillator is tuned with the ganged tuning capacitor, C3. A parallel trimmer capacitor, C24, assures tracking at high frequencies. A series padder capacitor, C25, is used for low frequency tracking; it is made adjustable by means of a small parallel trimmer, C26.

Mixer

The RF and local oscillator frequencies are mixed in the pentagrid mixer tube, V2. The RF signal is fed to grid 1 of the mixer tube from the tuned input circuits of T2 and C2. Tuning capacitor C2 is ganged with the RF and oscillator tuning capacitors for single-control tuning. The local oscillator signal is applied to grid 3 of the mixer tube. The RF and local oscillator frequencies are mixed in the electron stream of the mixer tube, producing a number of sum and difference frequencies in the plate output circuit. The IF transformer, T3, in the plate circuit of the mixer tube is tuned to the difference frequency (IF) present in the output of the tube.

IF Amplifier

A conventional IF stage is used, consisting of IF amplifier tube V3, input IF transformer T3, and output IF transformer T4. Both transformers are tuned to the intermediate frequency (456 kHz). The IF signal is coupled through T3 to the control grid of the pentode IF amplifier tube, V3. The amplified output from the plate of the tube is coupled through IF output transformerT4 to the diode detector stage.

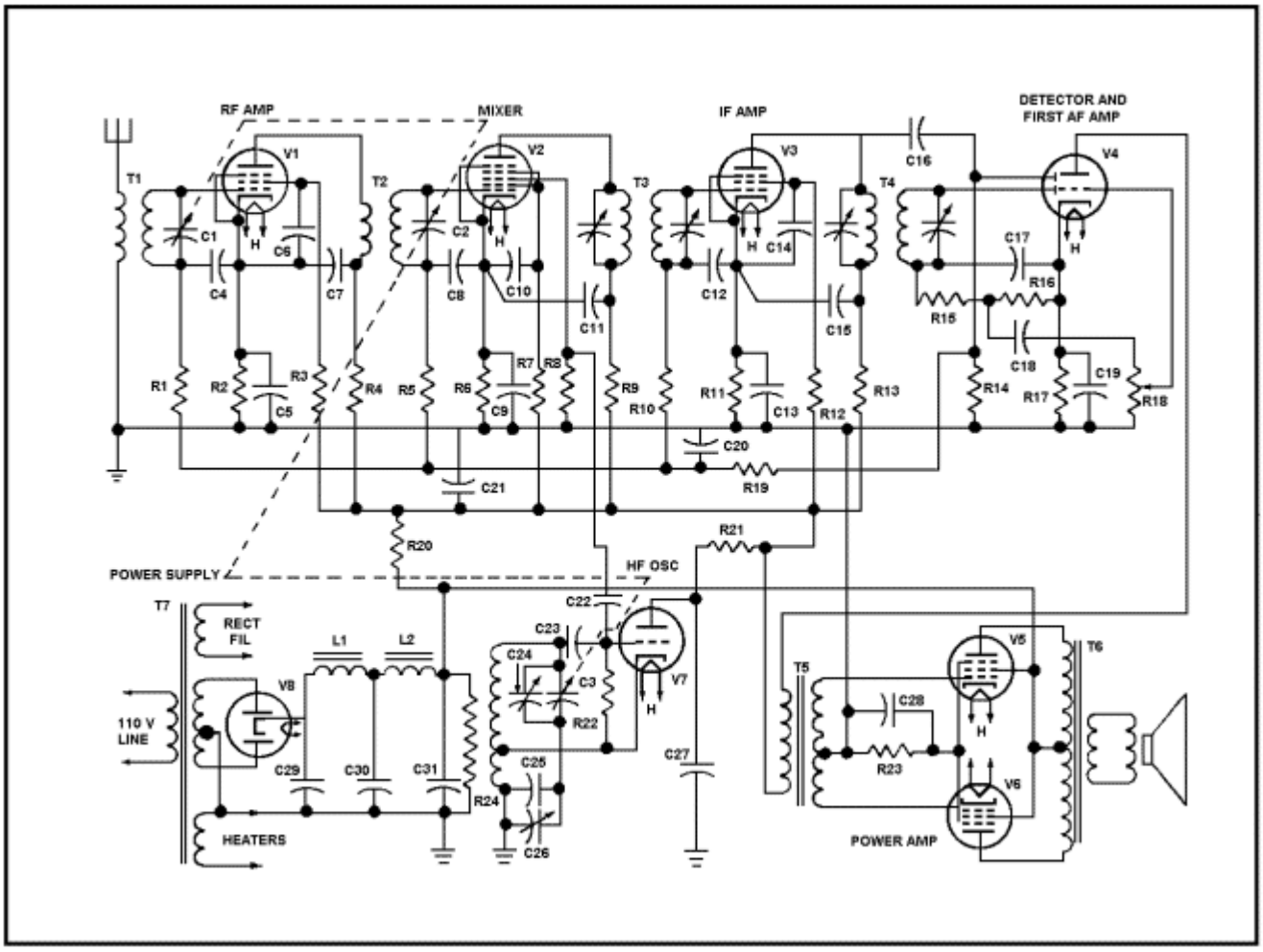

Figure 7-6 Typical Superheterodyne Circuit.

Detector, AVC, and First Audio-frequency Amplifier

A duplex diode-triode V4 is used in this stage to combine the functions of a diode detector, AVC, and first AF amplifier. The IF signal is coupled through IF transformer T4 to the lower diode section of V4, which acts as the detector. Series resistors R15 and R16 form the detector load resistance, and C17 is the load capacitor. The audio output from the detector is tapped off at the junction of R16, and R16 is coupled through blocking capacitor C18 and volume control R18 to the grid of the triode amplifier portion of V4. The volume control is a tapped variable resistor to permit feeding any portion of the AF output voltage to the grid of V4. The AF signal is amplified by the tube and is coupled to the power amplifier through interstage coupling transformers T5. IF voltage from the plate of the preceding IF amplifier also is fed through blocking capacitor C16 to the upper diode section of V4, which rectifies the signal voltage for AVC purposes. R14 is a separate AVC diode load resistor. The dc AVC voltage developed across this resistor is applied to the grids of RF amplifier V1, mixer V2, and IF amplifier V3 through AVC filters R19 and R20, which eliminates the audio component from the rectified AVC voltage.

AF Power Amplifier

The audio output from the plate of V4 is fed to the grids of the power amplifier pentodes, V5 and V6, through the interstage coupling transformer, T5. This transformer is center tapped to apply the audio signal in opposite phase relation to the grids of the two tubes, a necessary condition for push-pull operation. The output from the power amplifier is coupled to the voice coil of the loudspeaker through the center-tapped output transformer, T6. The transformer assures a correct match between the voice-coil impedance and the recommended plate-to-plate load impedance of the amplifier.

Power Supply

The 110-volt, 60-hertz ac line input is coupled to the plates of full-wave rectifier tube V8 through power transformer T7. The transformer carries additional windings to supply the rectifier filament and the heaters of the receiving tubes. The pulsating dc output from the rectifier tube is applied to a two-stage capacitor input filter consisting of filter capacitors C29, C30, and C31, and filter chokes L1 and L2. A bleeder resistor, R24, is connected across the filter output to provide a minimum load and improve the voltage regulation.

FREQUENCY TRACKING

The mixer and oscillator circuits of a superheterodyne are said to track when they maintain a constant frequency difference (IF) between them through-out the tuning range. To assist in tracking, the two variable capacitors are ganged together. Since the oscillator circuit is generally set to a frequency higher than that of the mixer and RF circuits, the capacitance and inductance of its tuned circuit must be smaller.

Also, for the higher oscillator frequency, the percentage of frequency shift for the oscillator tuning capacitor must be smaller for the same tuning range than that of the mixer and RF capacitors. This is achieved in some receivers by using a smaller coil and a smaller tuning capacitor with specially shaped plates in the oscillator circuit. The special shape of the plates ensures tracking throughout one frequency band. This method cannot be used, however, in multiband receivers, since each band requires a differently shaped oscillator tuning capacitor.

More commonly, the same size tuning capacitors are used for both oscillator and mixer circuits. The required frequency difference is made up with a smaller oscillator coil, and tracking is attained with trimmer and padder capacitors. The trimmer is connected parallel to the oscillator tuning capacitor, and the padder is connected in series with it (figure 7-7). At the highfrequency end of the tuning range, the oscillator tuning capacitor is set for minimum capacitance. The parallel trimmer has about the same order of magnitude as this minimum value, and its adjustment determines the proper resonant frequency at this end of the frequency range.

At the low-frequency end of the tuning range, the capacitance of the oscillator tuning capacitor is near maximum and, therefore, the small parallel trimmer is negligible in comparison with it. However, the series padder is usually about two to four times the magnitude of the maximum oscillator tuning capacitance. Since the total capacitance of two-series capacitors is influenced chiefly by the smaller of the two capacitors, the effect of the series padder on the total tuning capacitance at the low-frequency end is not very great but suffices to set the resonant frequency within the limits required for proper tracking. By proper adjustment of the padder and trimmer capacitors, reasonable tracking accuracy can be attained throughout the frequency range. If several bands are utilized, separate trimmer and padder capacitors usually are provided for each band.

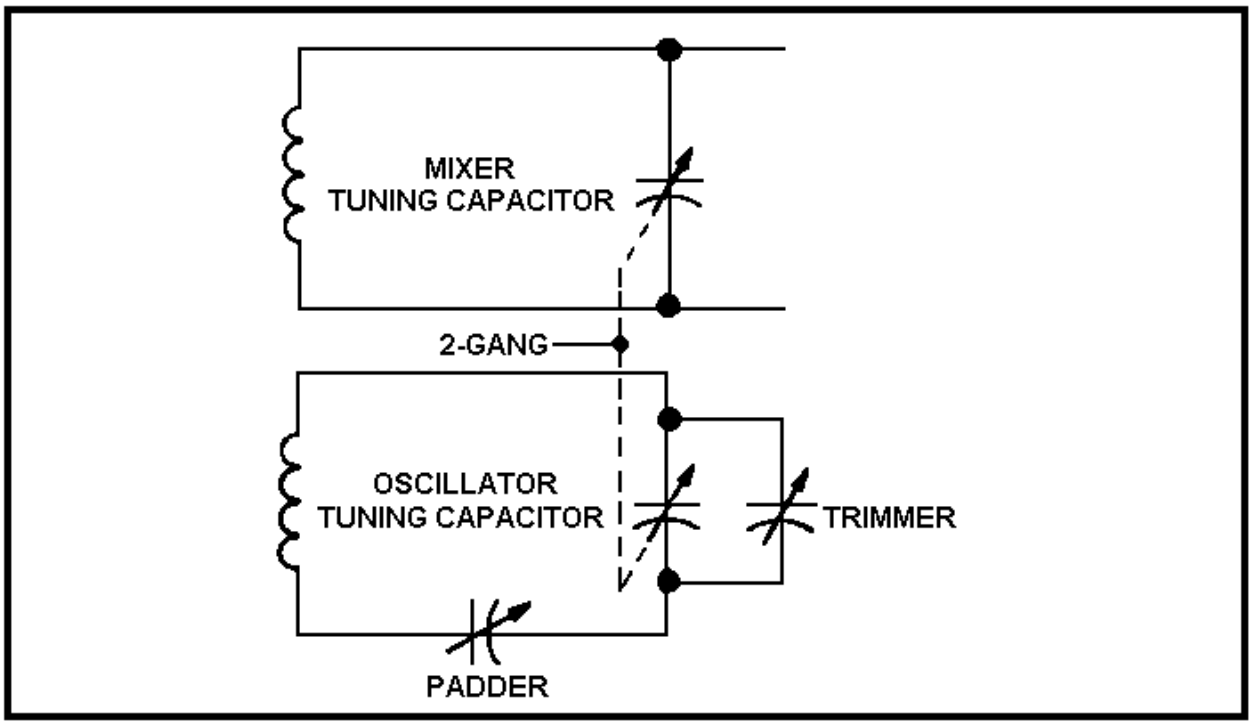

Figure 7-7. Padder and Trimmer Connections.

Figure 7-7. Paddar and Trimmer Connections.

SELECTIVITY OF SUPERHETERODYNES

The selectivity of each IF stage depends on the Q and the coupling of the IF transformer. The overall selectivity of the IF amplifier is proportional to the number of tuned circuits (IF transformers) utilized. The total selectivity increases as the product of the number of stages in a manner similar to that for the tuned RF amplifier. Overall selectivity also increases if the IF used is lowered. The exact IF amplifier selectivity of military receivers varies widely, depending on the specific use to which the receiver is put. Most communication receivers have variable IF selectivity. A switching arrangement permits several amounts of fixed selectivities to be obtained. In one receiver, for example, a three-position switch is used to produce a total IF band-pass of 10 kHz, 6 kHz, and 3 kHz.

SELECTION OF INTERMEDIATE FREQUENCY

The selection of the IF is a compromise between various conflicting factors. The higher the IF, the lower is the selectivity and the gain of the stage. On the other hand, it is impractical for the IF to be substantially lower than the signal frequency. This is because trouble results from image interference if the difference between the signal frequency and the IF is made very great. A low IF also increases the undesirable interaction between the signal and oscillator frequencies. Although the selectivity and gain for low intermediate frequencies are excellent, image interference and pulling must be taken into account.

The selection of the IF is a careful compromise between the desired selectivity and gain and the permissible image interference and amount of pulling. For amplitude modulated (AM) reception up to approximately 10 MHz, intermediate frequencies from 455 to 465 kHz have been found satisfactory. An IF of 455 to 465 kHz generally is used for AM communication receivers.

IF TRANSFORMER CONSTRUCTION

The IF transformer circuits are contained in a metal shield container in which the coils and tuning capacitors are mounted. The capacitors can be made of mica, or they can be air-trimmer capacitors. The coils may have an air core, or a powdered-iron core, the latter providing somewhat greater Q. Powdered-iron cores can be tuned by moving the core in or out of the coil, thus varying the inductance. This is called permeability, or slug, tuning. With permeability tuning, a fixed mica capacitor can be used. The frequency stability or permeability tuning is comparable to that of variable-tuned air capacitors. Stability is important to prevent frequency drift, which reduces the gain and selectivity of the IF stage. Small protruding adjusting shafts permit tuning the transformer outside of the case.

AUTOMATIC VOLUME CONTROL

Although manual volume controls permit regulating the gain of a receiver to a convenient output level, it is desirable to have additional automatic control of the receiver gain for several reasons. One reason is that it prevents extreme variations in loudspeaker volume.

When a receiver is turned from a weak station (for which the volume has been turned up) to a strong station, the loudspeaker sound will blast unpleasantly. The variations in signal strength of a signal carrier because of fading and other conditions will also result in wide fluctuations of the loudspeaker volume. Furthermore, variations in signal strength at the antenna, if not compensated for, can cause serious trouble by overloading the RF, IF, or detector stage of the receiver that, in turn, results in distortion of the signal. An automatic volume control circuit overcomes these troubles by automatically regulating the gain of the RF and IF stages. By making the gain of these stages less for a strong signal than for a weak signal, constant signal input can be maintained at the detector regardless of signal strength at the antenna. The output volume from the speaker then will depend only on the degree of modulation at the transmitter.

Circuit Operation

The RF, IF, and mixer stages of a receiver utilize remote cutoff tubes whose gain can be controlled by varying their grid bias. By making the grid bias of these tubes more negative, the stage gain is reduced. If the gain of several stages is controlled by a negative bias voltage, the value of which depends on signal strength (AVC voltage), ample reduction in receiver sensitivity can be attained for strong signals. The gain of the receiver, however, never can be increased beyond its maximum value in the absence of AVC. The AVC circuit simply provides this negative bias voltage, whose magnitude is proportional to signal strength, for reducing receiver gain.

Figure 7-8 shows the addition of an AVC circuit to the diode detector. When the diode current flows through the load resistance, R, it generates a voltage drop that makes the left end of R negative in respect to ground. This negative voltage drop is applied through filter circuit R_1C_1 to bias the grids of the preceding stages that are to be controlled. When the signal strength increases, the bias voltage developed across R also increases because of the greater average rectified diode current; therefore, the gain of the controlled stages is reduced. As a result, the output of the last IF stage to the detector is increased only slightly for a large increase in signal level. For a decrease in signal level from the previously steady value, the action is reversed. The AVC bias decreases, and the gain of the amplifier stages and the detector increases. The AVC circuit always tends to counteract changes in signal level at the antenna of the receiver.

The filter circuit, R_1C_1, prevents the AVC bias from varying at an audiofrequency rate. Load resistance R and capacitor C of the detector are designed to filter out IF and RF variations so that the voltage across them varies only at the audio-frequency rate of the modulation. If the AVC were taken directly from R without filter R_1C_1, the individual AF variations of the AVC voltage would vary the receiver gain, thus tending to counteract the modulation of the carrier and produce distortion. Filter R_1C_1 is designed to prevent this from happening by smoothing out the AF variations in the AVC voltage so that it does not follow the modulation and is substantially constant. The AVC voltage, therefore, cannot vary as fast as the audio-range frequencies, but acts rapidly enough to compensate for the slower amplitude variations caused by signal fading and changes in tuning from one station to another.

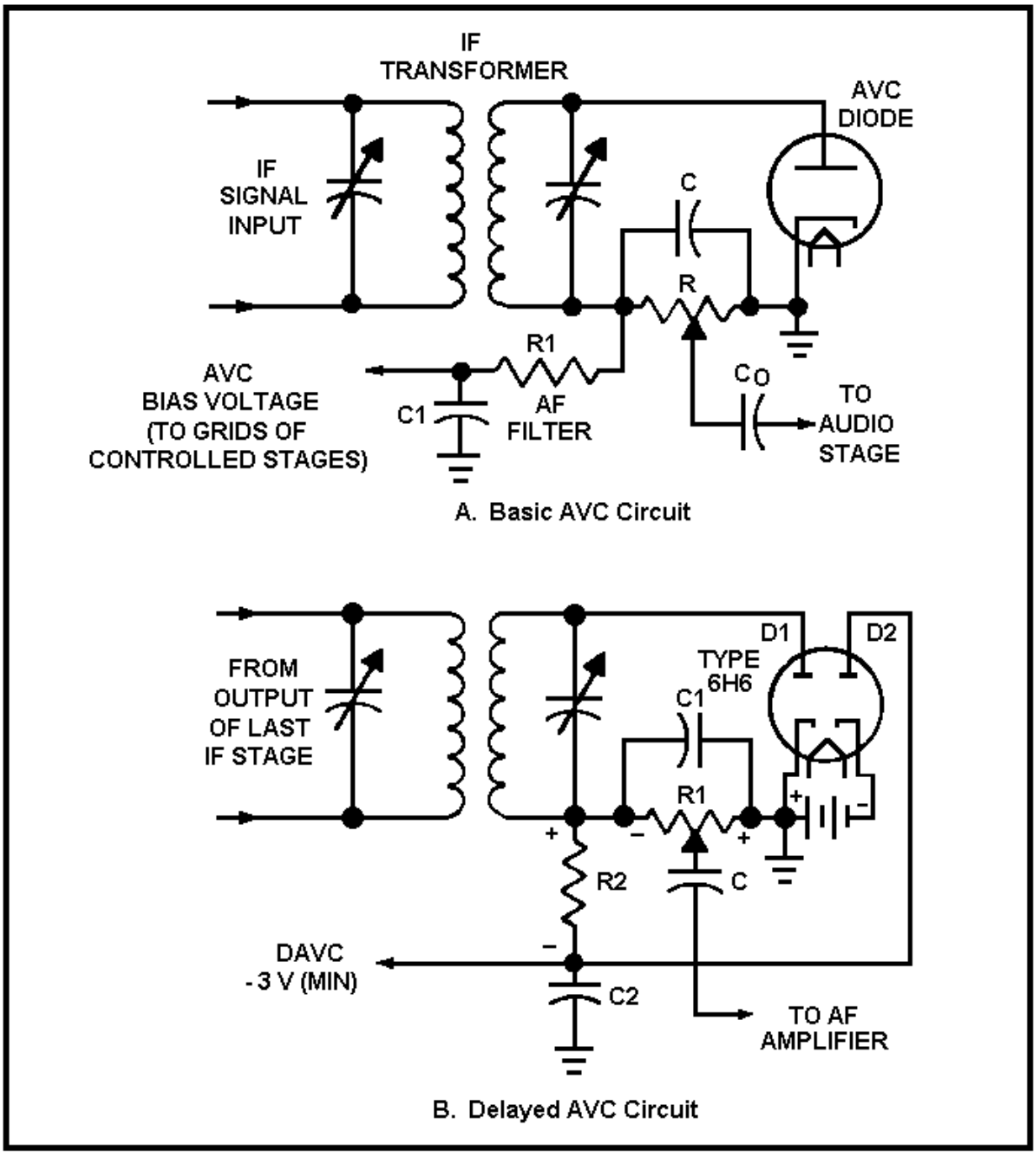

Figure 7-8. Automatic Volume Control Circuits.

Figure 7-8. Automatic Volume Control Circuits.

Delayed Automatic Volume Control

In the circuit shown in A of figure 7-8, a certain amount of AVC bias is developed even for weak signal inputs. In many applications, however, it is desirable to have maximum RF and IF gain available for weak signals. Some communication receivers permit switching off the AVC with a manual cutoff switch when it is desired to

have maximum sensitivity available. This can be achieved automatically by means of a DAVC (delayed AVC) circuit, which prevents the application of AVC bias until the signal strength exceeds a certain predetermined value.

In B of figure 7-8, the diode section, D1, of the twin diode acts as a detector and AVC diode. R1 and C1 are the diode load resistance and filter capacitor, respectively, while R2 and C2 act as an AVC filter to smooth out the audio variations so that the AVC bias will be relatively constant for these frequencies. The audio output from the detector is taken from a tap on load resistance R1 and is coupled through C to the grid of the first audio amplifier stage. The cathode of diode section D2 is returned through a fixed supply voltage of -3 volts to the cathode of D1 and ground. This fixed voltage can be supplied by a small bias cell or by connecting the cathode of D2 to a tap on a power supply voltage divider. Because of the presence of the fixed voltage, a direct current flows through R1 and R2 in series with diode D2. The voltage drop caused by this current places the AVC tap at the lower end of R2 at approximately -3 volts, since the voltage drop across D2 is negligibly small. The -3-volt fixed bias is approximately the proper minimum value for maximum sensitivity of the remote cutoff tubes.

For signals that are not strong enough to develop a rectified voltage across R1 in excess of 3 volts, the AVC bias to the controlled tubes remains constant at -3 volts. For strong signals, however, the average value of the rectified signal voltage across R1 exceeds 3 volts and thus cancels out the fixed -3-volt bias. Consequently, for signals exceeding 3 volts, the plate voltage at D2 becomes negative in respect to the cathode, and current stops flowing through D2. The AVC voltage, then, is controlled solely by the rectified signal voltage developed across R1. Any further increase of the rectified signal voltage beyond 3 volts then progressively increases the AVC bias to the controlled stages thus reducing their gain.

REVIEW EXERCISES

Circle the letter of the correct answer to each question.

1. What stage in a superheterodyne receiver is not absolutely necessary?

   a. IF amplifier.
   b. Detector.
   c. Converter.
   d. RF amplifier.

2. What is a disadvantage of the TRF receiver?

   a. Gain decreases sharply at low frequencies.
   b. Selectivity decreases sharply at low frequencies.
   c. Selectivity increases too sharply at high frequencies.
   d. Gain decreases too sharply at high frequencies.

3. What is an advantage of the superheterodyne over the TRF receiver?

   a. It has greater amplification with feedback and oscillation.
   b. It has more variable-tuned circuits.
   c. It has more fixed-tuned circuits.
   d. It has greater amplification without feedback and oscillation.

4. What signal frequency is applied directly to the loudspeaker?

   a. Radio.
   b. Audio.
   c. Video.
   d. Stereo.

5. What is a typical IF frequency, in kHz, for amplitude modulation?

   a. 4.5 kHz.
   b. 45 kHz.
   c. 455 kHz.
   d. 4,500 kHz.

6. What stage develops the AVC voltage?

   a. Mixer.
   b. Converter.
   c. Detector.
   d. Separator.

7. What stage removes the radio frequencies from the audio frequencies in a superheterodyne receiver?

   a. Detector.
   b. Converter.

c. Limiter.
d. Clipper.

8. What circuits convert the RF signal to an IF signal?

a. AF and mixer.
b. IF and oscillator.
c. Mixer and oscillator.
d. Converter and oscillator.

9. What normally determines the selectivity of each IF stage in a superheat erodyne receiver?

a. Z and coupling of the IF transformer.
b. Q and coupling of the IF transformer.
c. R and coupling of the RF transformer.
d. L and coupling of the RF transformer.

10. What is a major disadvantage of using a low-intermediate frequency?

a. Low selectivity.
b. Low gain.
c. High-image rejection.
d. Pulling of the local oscillator.

11. What bandwidth, in kHz, is necessary for faithful reproduction of music and speech?

a. 10 kHz.
b. 15 kHz.
c. 20 kHz.
d. 25 kHz.

12. What operational feature makes diode detectors preferable in superheterodyne receivers?

a. High-gain output.
b. Linear characteristic.
c. High-signal output.
d. Nonlinear characteristic.

13. How many prominent frequencies are produced if two sine waves are applied to a mixer at different frequencies?

a. One.
b. Two.
c. Three.
d. Four.

14. What type of coupling is used between the antenna and the RF amplifier?

a. Capacitor.
b. Inductor.
c. Impedance.
d. Transformer.

15. Where does most signal amplification occur in a superheterodyne receiver?

    a. RF stage.
    b. IF stage.
    c. Converter stage.
    d. Detector stage.

Recheck your answers to the Review Exercises. When you are satisfied that you have answered every question to the best of your ability, check your answers against the Exercise Solutions. If you missed more than one question, you should retake the entire lesson, paying particular attention to the areas in which your answers were incorrect.

MM 0705

EXERCISE SOLUTIONS

Lesson 1, Basic Vacuum Tubes	Lesson 2, Special Purpose Tubes	Lesson 3, Power Supplies
1. c (see page 1).	1. b (see page 59).	1. a (see page 79).
2. b (see page 40).	2. d (see page 60).	2. c (see page 80).
3. b (see page 19).	3. a (see page 49).	3. a (see page 82).
4. d (see page 41).	4. b (see page 48).	4. c (see page 83).
5. d (see page 28).	5. a (see page 68).	5. b (see page 81).
6. a (see page 3).	6. a (see page 61).	6. a (see page 85).
7. b (see page 20).	7. b (see page 46).	7. b (see page 86).
8. a (see page 27).	8. c (see page 59).	8. b (see page 86).
9. a (see page 34).	9. c (see page 51).	9. d (see page 88).
10. a (see page 41).	10. b (see page 63).	10. c (see page 90).
11. C (see page 27).	11. a (see page 56).	11. c (see page 90).
12. b (see page 34).	12. c (see page 47).	12. c (see page 90).
13. d (see page 18).	13. c (see page 62).	13. b (see page 92).
14. d (see page 40).	14. b (see page 58).	14. a (see page 93).
15. b (see page 36).	15. c (see page 51).	15. c (see page 94).
16. c (see page 30).	16. b (see page 52).	16. c (see page 94).
17. c (see page 23).	17. c (see page 71).	17. b (see page 99).
18. c (see page 19).	18. a (see page 46).	18. d (see page 99).
19. b (see page 32).	19. a (see page 59).	19. d (see page 106).
20. a (see page 8).	20. d (see page 54).	20. c (see page 108).
21. b (see page 14).	21. c (see page 60).	21. a (see page 110).
22. b (see page 41).	22. c (see page 64).	22. b (see page 111).

23. b (see page 38).
24. d (see page 33).

23. b (gee page 71).
24. d (see page 50).
25. a (see page 51).

23. b (see page 115).
24. d (see page 116).
25. d (see page 120).
26. a (see page 122).
27. c (see page 124).

Lesson 4, Amplifiers

1. d (see page 136).
2. d (see page 142).
3. b (see page 150).
4. a (see page 143).
5. a (see page 138).
6. c (8ee page 143).
7. b (see page 134).
8. d (see page 146).
9. c (see page 147).
10. d (see page 148).
11. a (see page 149).
12. a (see pages 148 and 149).
13. c (see page 150).

Lesson ,Oscillators

1. b (see page 159).
2. a (see page 166).
3. d (see page 156).
4. c (see page 173).
5. c (see page 173).
6. d (see page 159).
7. b (see page 161).
8. b (see page 162).
9. d (see page 162).
10. a (see page 155).
11. b (see page 167).
12. d (see page 171).
13. c (see page 166).
14. b (see page 159).
15. c (see page 165).

Lesson 6, Amplitude Modulation

1. c (see page 179).
3. b (see page 180).
4. a (see page 185).
5. a (see page 183).
6. c (see page 183).
7. b (see page 187).

Lesson 7, Superheterodyne Receivers

1. d (see page 195).
2. d
3. d (see page 191).
4. b (see page 199).
5. c (see page 204).
6. c (see page 202).
7. a (see page 199).

8. b (see page 184).

9. a (see page 186).

10. d (see page 186).

8. c (see page 195).

9. b (see page 204).

10. d (see page 204).

11. a (see page 198).

12. b (see page 198).

13. d (see page 196).

14. d (see page 195).

15. b (see page 195).

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